The Science of the (Jefferson Lab) Electron-Ion Collider

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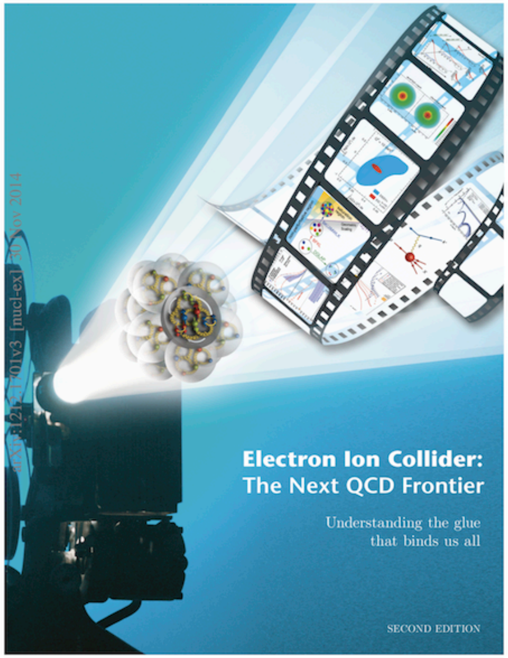
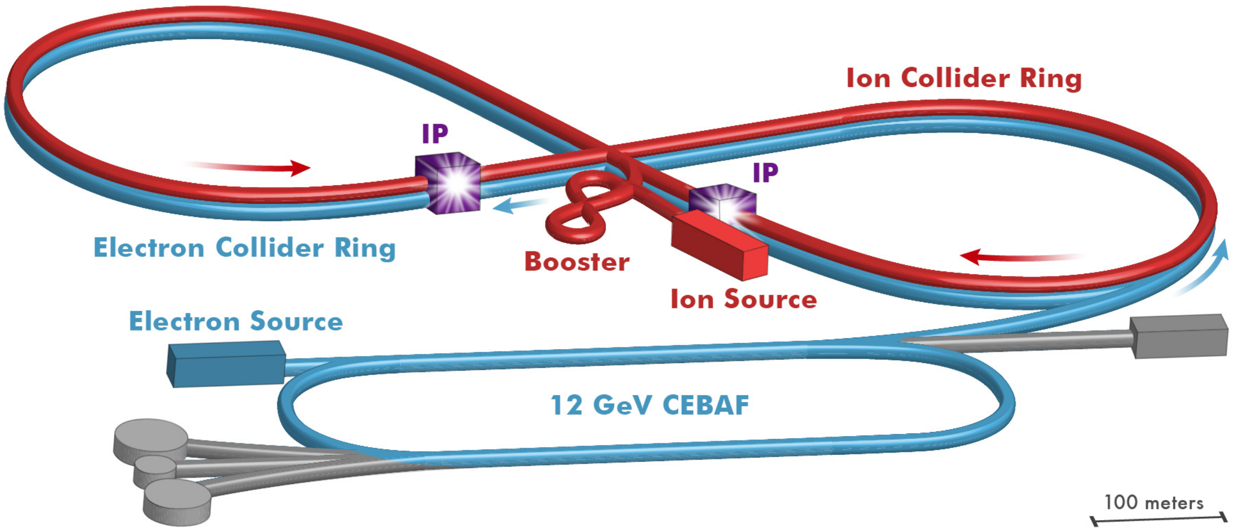




Fermilab Joint Experimental-Theoretical Physics Seminar, July 8th 2016

Outline

Nuclear Physics (NP)

Roadmap of matter: study fundamental building blocks of matter (quarks and gluons, protons, atomic nuclei)

1 – Cool facts about QCD and nuclei

2 – Experimental NP in a nutshell

NP vision: Electron-Ion Collider

next-generation U.S. facility to study quarks and gluons in strongly interacting matter

3 – The Electron-Ion Collider project

Jefferson Lab

- U.S. DOE **national laboratory** in the City of Newport News, VA
- **NP mission:** conduct research that builds a comprehensive under-standing of the atom's nucleons

JLEIC

Jefferson Lab Electron-Ion Collider

4 – Accelerator design

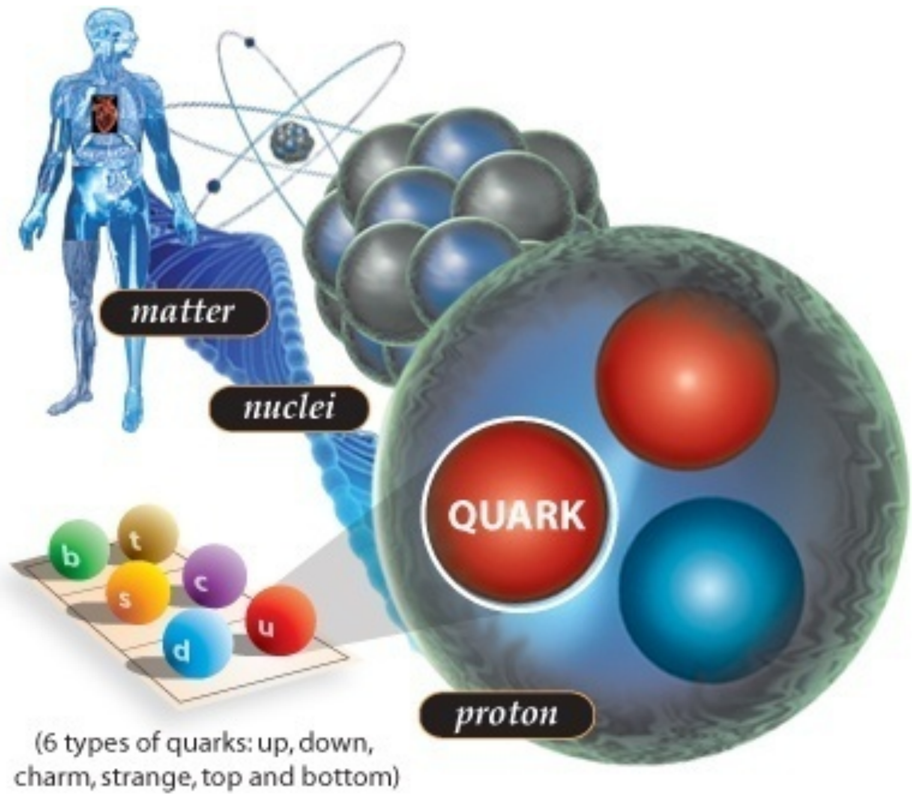
5 – Detector design

Prologue

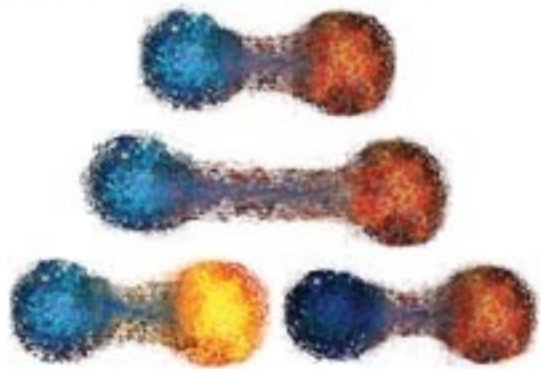
Cool facts about QCD and nuclei

Cool facts about QCD and nuclei

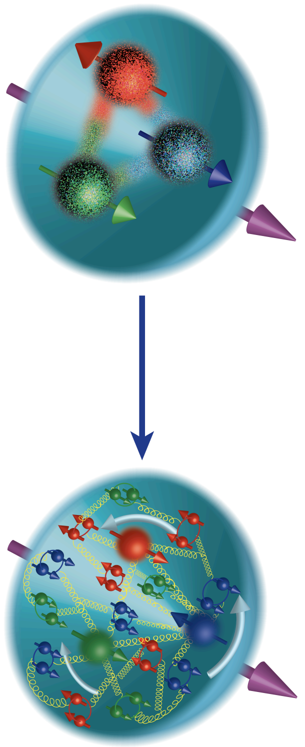
- If an atom was the size of a football field, the (atomic) nucleus would be about the size of a football.
- Despite its tiny dimensions, the nucleus accounts for 99.9% of an atom's mass.
- Protons and neutrons swirl in a heavy atomic nucleus with speeds of **up to some ¾ of c**. More commonly, their speed is some ¼ the speed of light. The reason is because they are *strong-forced* to reside in a small space.
- Quarks (and gluons) are *confined* to the even smaller space inside protons and neutrons. Because of this, they swirl around with **the speed of light**.



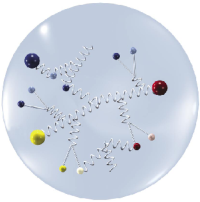
Cool facts about QCD and nuclei

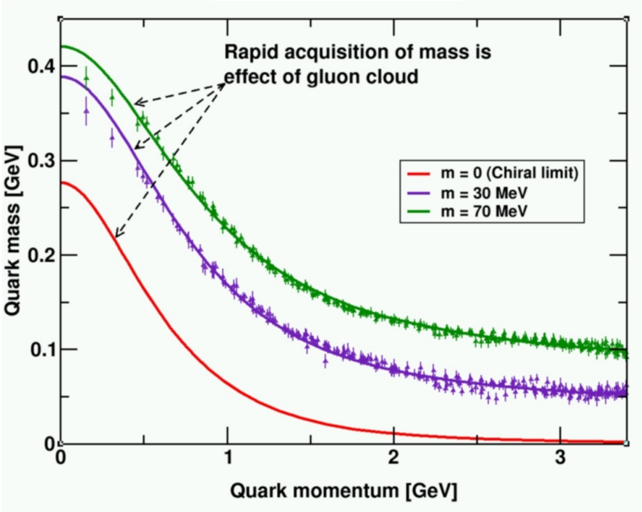


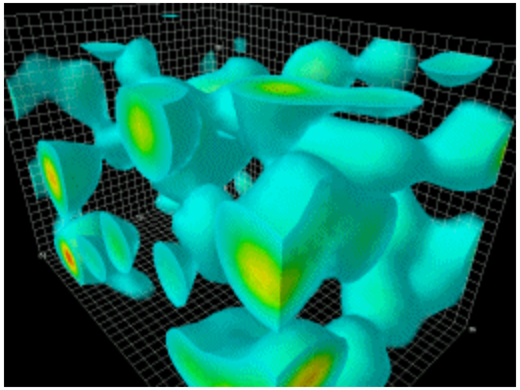
- The strong force is so strong, that you can never find one quark alone (this is called **confinement**).
- When pried even a little apart, quarks experience ten tons of force pulling them together again.
- Quarks and gluons jiggle around at nearly light-speed, and extra gluons and quark/anti-quark pairs pop into existence one moment to disappear the next.
- This flurry of activity, fueled by the energy of the gluons, **generates nearly all the mass of protons and neutrons**, and thus ultimately of all the matter we see.
- Even the QCD *vacuum* is not truly empty. Long-distance gluonic fluctuations are an integral part. Quarks have small mass themselves, but attain an effective larger mass due to the fact that they attract these gluonic fluctuations around them.
- Nuclear physicists are trying to answer how basic properties like mass, shape, and spin come about from the flood of gluons, quark/anti-quark pairs (the *sea*), and a few ever-present quarks.



QCD and the origin of mass



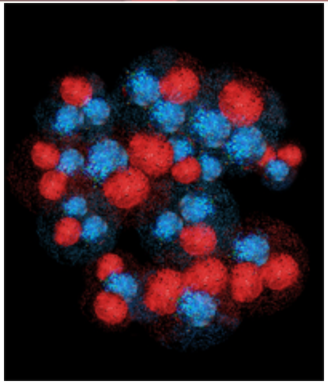


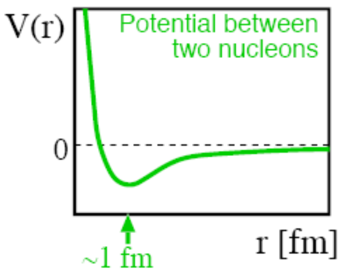


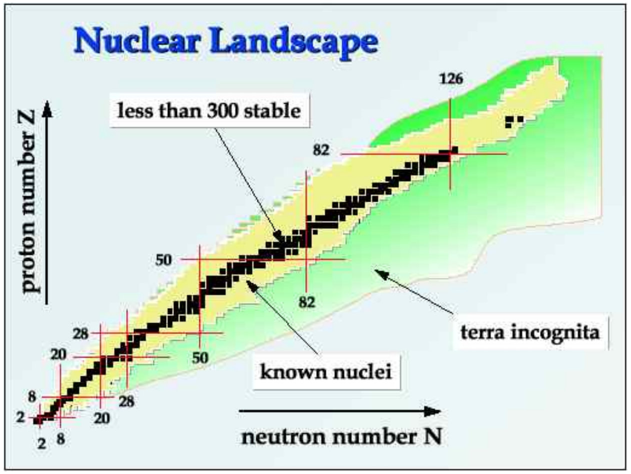
- Mass is an emergent phenomenon.
- Mass from massless gluons and nearly massless quarks
- Most of the proton's mass/energy is due to the self-generating gluon field and the quark-gluon interactions dynamically breaking chiral symmetry
  - Higgs mechanism has no role here.
- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Quarks contribute almost nothing.

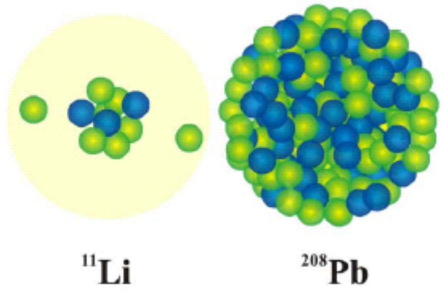
Cool facts about QCD and nuclei

- A small fraction of the force between quarks and gluons “leaks out” of protons and neutrons, and binds them together to form tiny nuclei. The long-range part of this process can be well described as if **protons and neutrons** exchange **pions**.
- Nuclear physicists are only now starting to understand how this ***leakage*** occurs, and how it results in the impressive variety of nuclei found in nature.
- A nucleus consisting of some 100 protons and 150 neutrons can be the same size as one with 3 protons and 8 neutrons.
- Despite the variety of nuclei found in nature, we believe we miss quite some more. These are necessary to explain the **origin of nuclei and the abundance of elements found in the cosmos**.





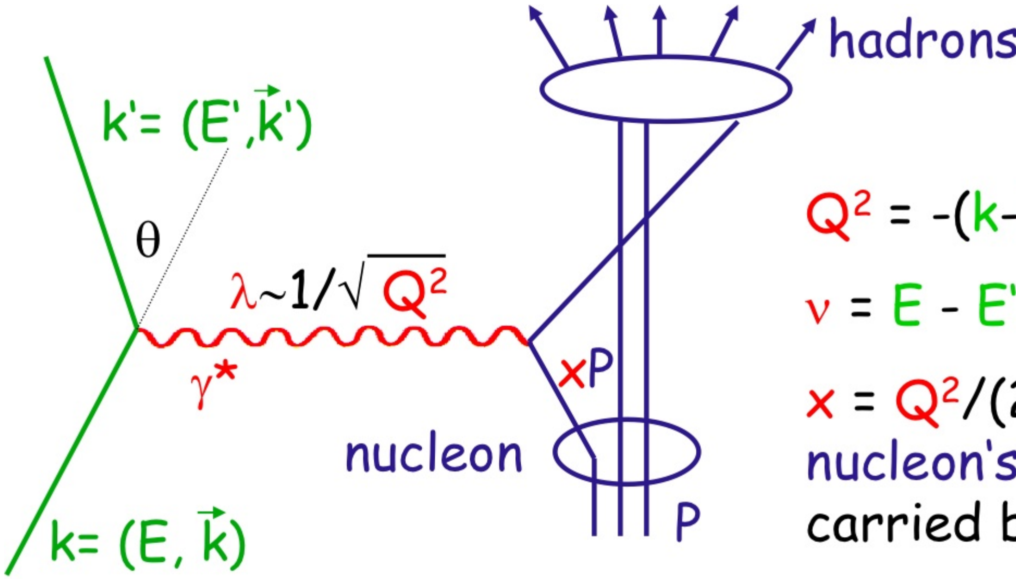




Introduction

Experimental Nuclear Physics in a nutshell

Deep-inelastic lepton-nucleon scattering



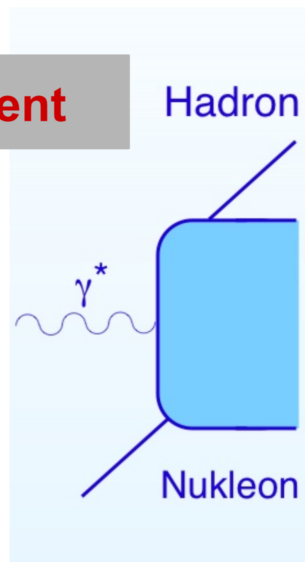
$Q^2 = -(k-k')^2 = 2EE'(1-\cos\theta)$

$\nu = E - E'$, $y = \nu/E$

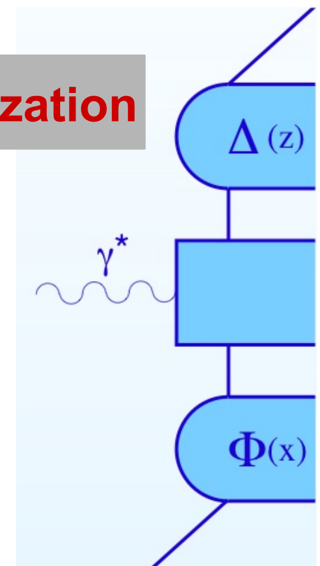
$x = Q^2/(2M\nu)$ = fraction of nucleon's momentum P, carried by struck quark

Measurement

cross section



QCD Factorization

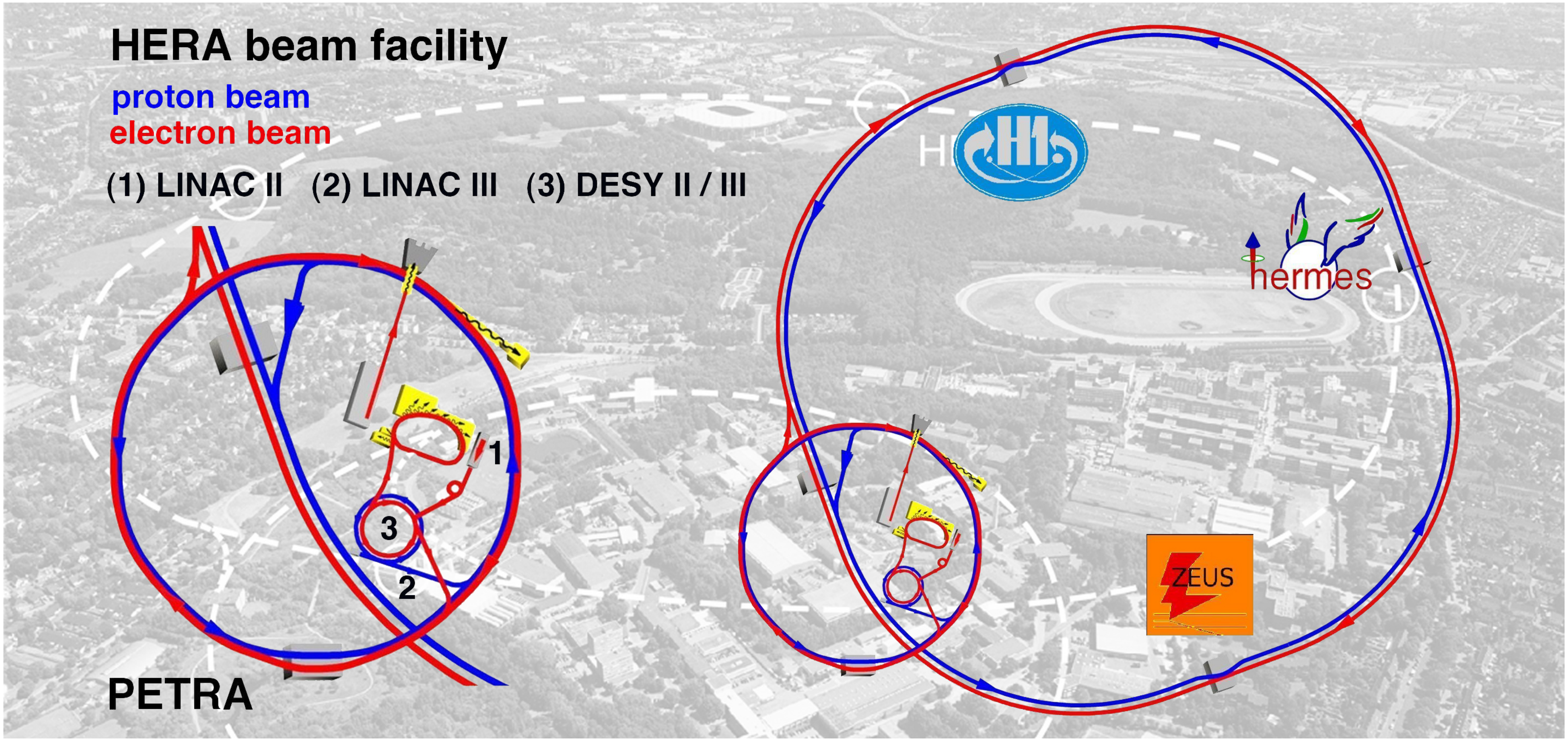


fragmentation

short-distance dynamics, calculable

confinement, **PDF**

HERA – The first Electron-Ion Collider



Parton distribution functions (PDF)

cross-section measurements

↓ decomposed

structure functions

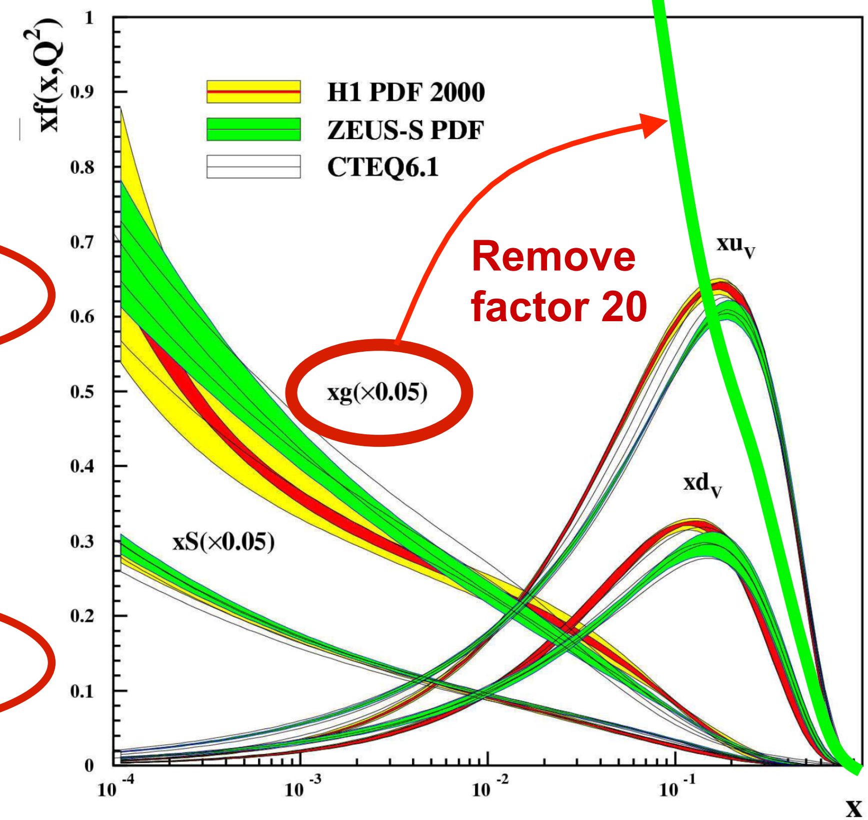
process dependent

↓ QCD analysis using QCD factorization theorem

PDFs

universal

$$F_1(x,Q^2) = \sum_q e_q^2 \left(f_1^q(x,Q^2) + f_1^{\bar{q}}(x,Q^2) \right)$$

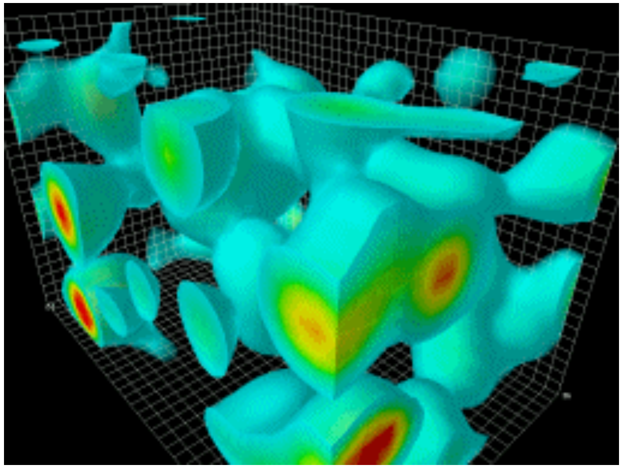


Section

The Electron-Ion Collider project

Gluons and QCD

- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei
- Gluons dominate the structure of the QCD vacuum.



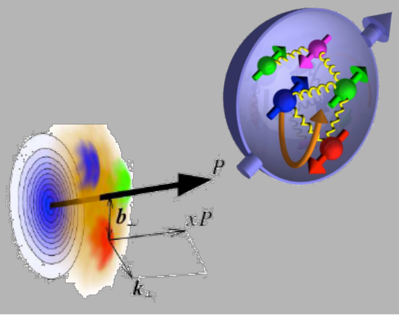
Facts:

- The essential features of QCD (e.g. asymptotic freedom, chiral symmetry breaking, and color confinement) are driven by gluons.
- Unique aspect of QCD is the self interaction of the gluons.
- Most of mass of the visible universe emerges from gluons.
- Half of the nucleon momentum is carried by gluons.

The most compelling science questions

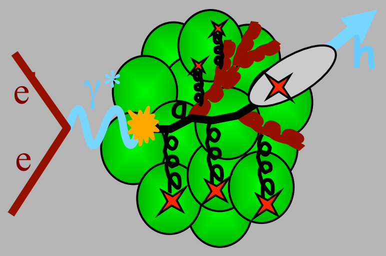
How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?

- How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
- What is the role of the motion of sea quarks and gluons in building the nucleon spin?



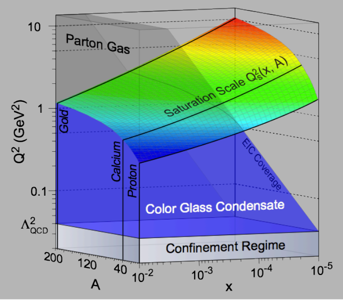
How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?

- How does the transverse spatial distribution of gluons compare to that in the nucleon?
- How does matter respond to fast moving color charge passing through it? Is this response different for light and heavy quarks?



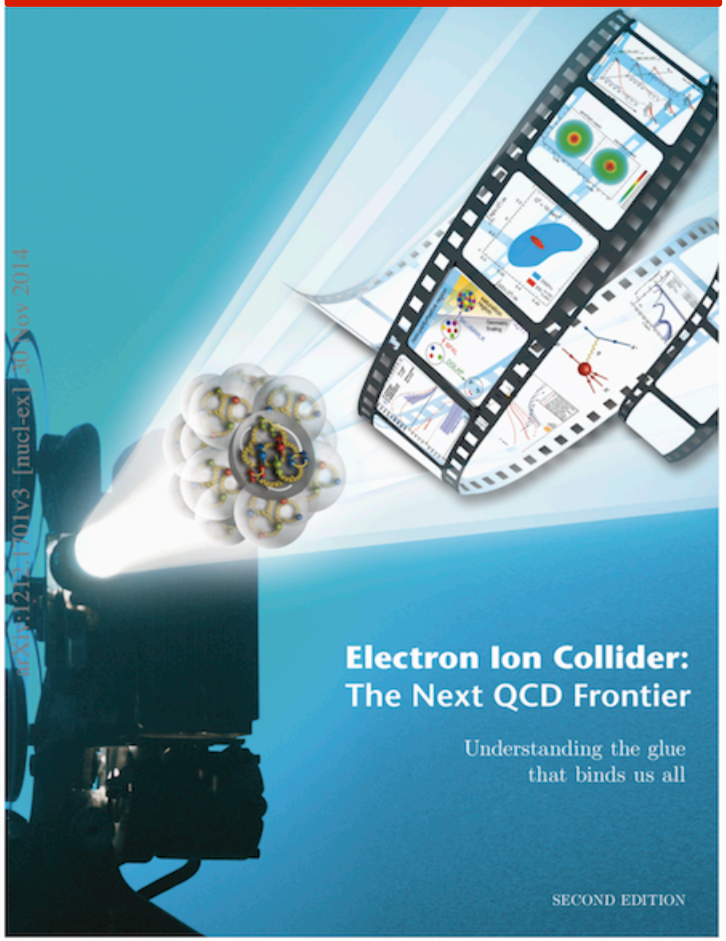
Where does the saturation of gluon densities set in?

- Is there a simple boundary that separates the region from the more dilute quark-gluon matter? If so how do the distributions of quarks and gluons change as one crosses the boundary?
- Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?



Electron-Ion Collider (EIC)

EIC White Paper: The glue that binds us all (**arXiv:1212.1701**)



World's first collider of:

- **polarized electrons** and **polarized protons/light ions**
- **electron-nucleus collider**

Realization of the science case:

- eRHIC at BNL
- **Jefferson Lab EIC** (this presentation)

For e-N collisions at the EIC:

- Polarized beams: **e, p, d, ^{3}He**
- **e** beam: 3-10 GeV
- L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}s^{-1} (10^2 – 10^3 times HERA)
- variable CM energy: 20-100 GeV

For e-A collisions at the EIC:

- wide range in nuclei
- luminosity per nucleon same as **e-p**
- variable CM energy

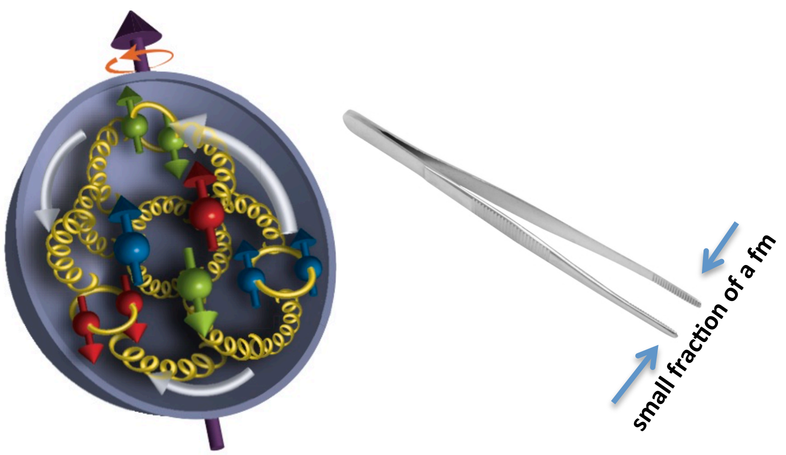
Section

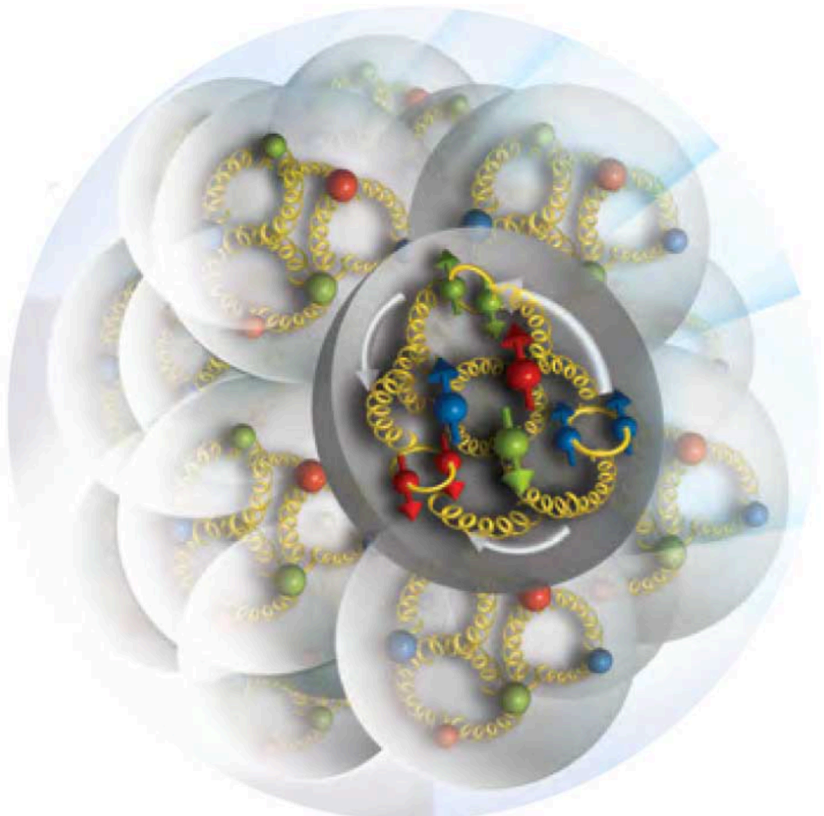
Accelerator Design – Designing the right probe

EIC physics program

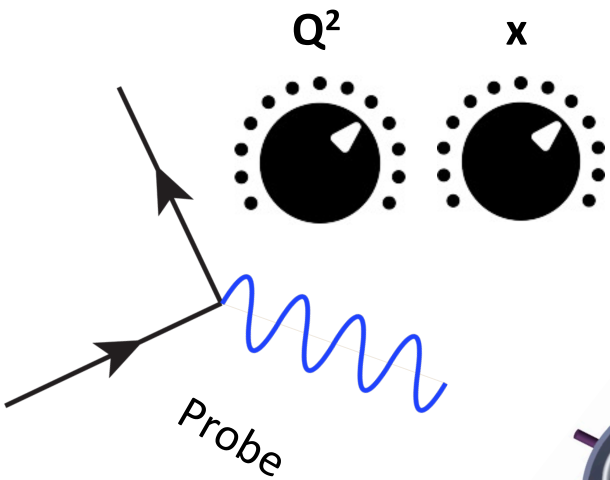
Program aim:

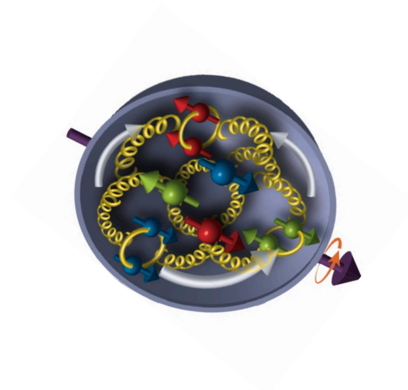
- Revolutionize the understanding of nucleon and nuclear structure and associated dynamics.
- For the first time, get (almost?) all relevant information about quark-gluon structure of the nucleon





Parameters of the Probe

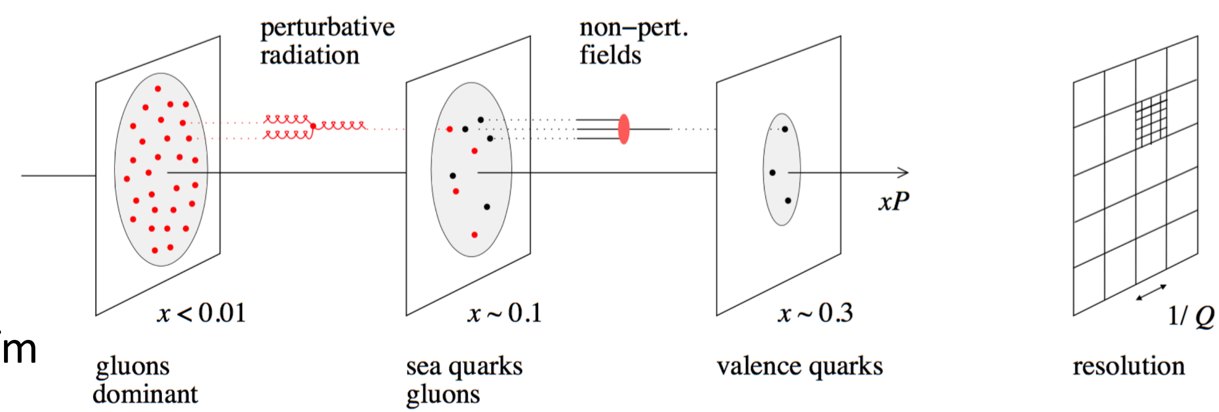




Ability to change **x** projects out different configurations where different dynamics dominate

Ability to change **Q^2** changes the resolution scale

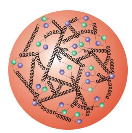
Q^2= 400 GeV^2 => 1/Q = .01 fm



Where EIC Needs to be in x (nucleon)

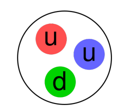
Saturation Regime: Needs to be Accessed via Ions

Collective Regime



Many-body Regime

Few-body Regime



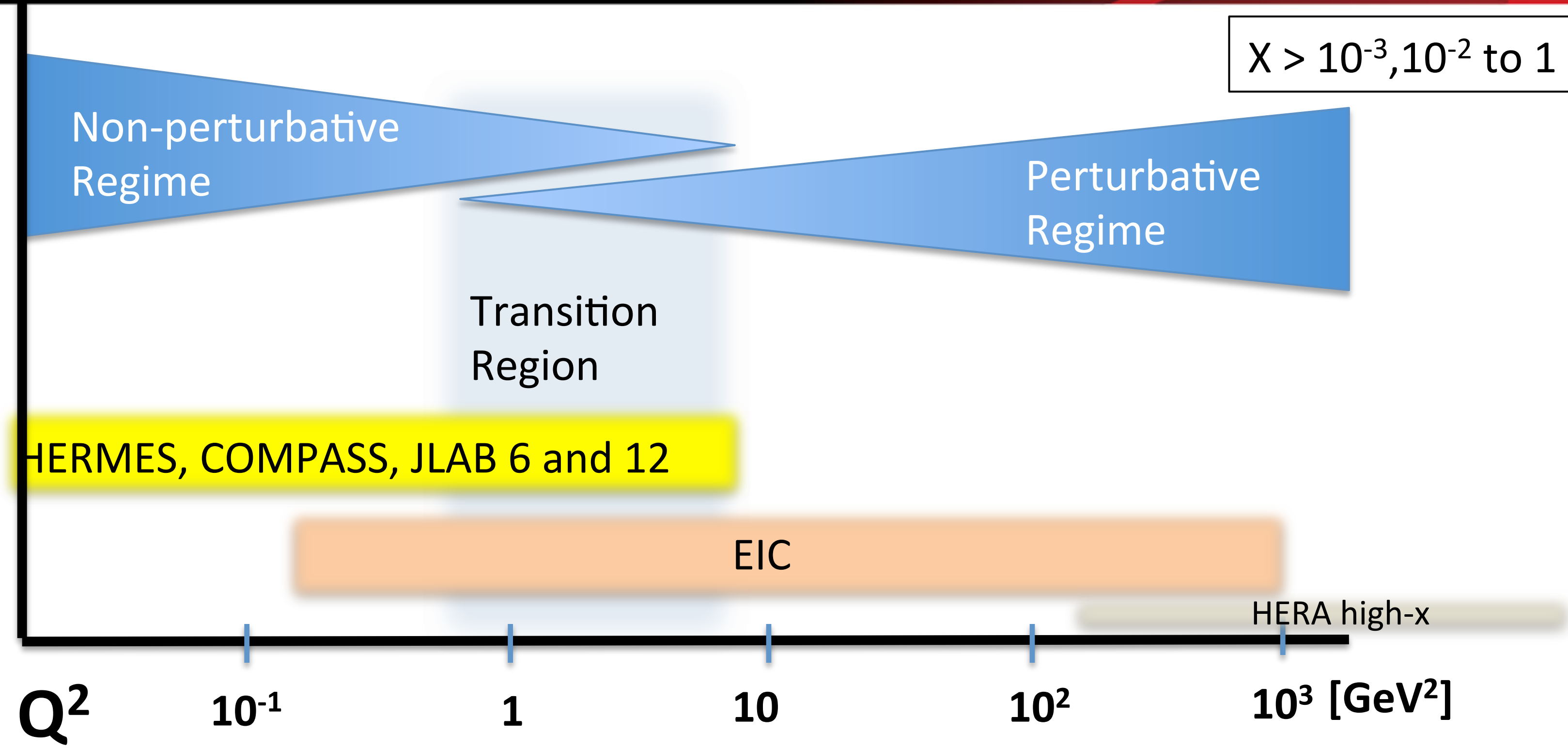
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 X (for proton)

QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

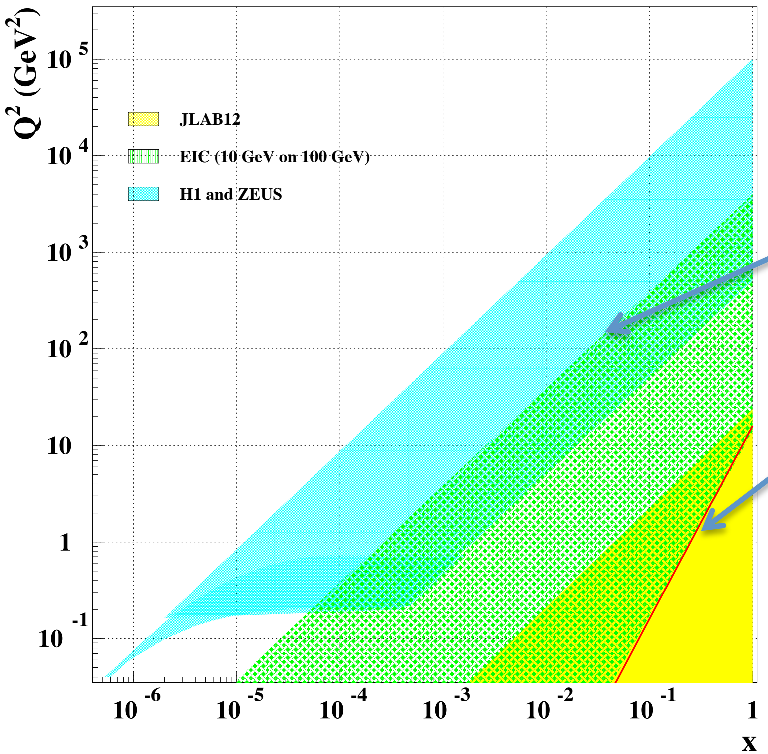
Where EIC needs to be in Q^2



- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

Disentangle Pert./Non-pert., Leading Twist/Higher Twist

JLEIC parameters (nucleon)



Cross section decreases rapidly with higher X

This edge determined by √s:
√s = 65 GeV

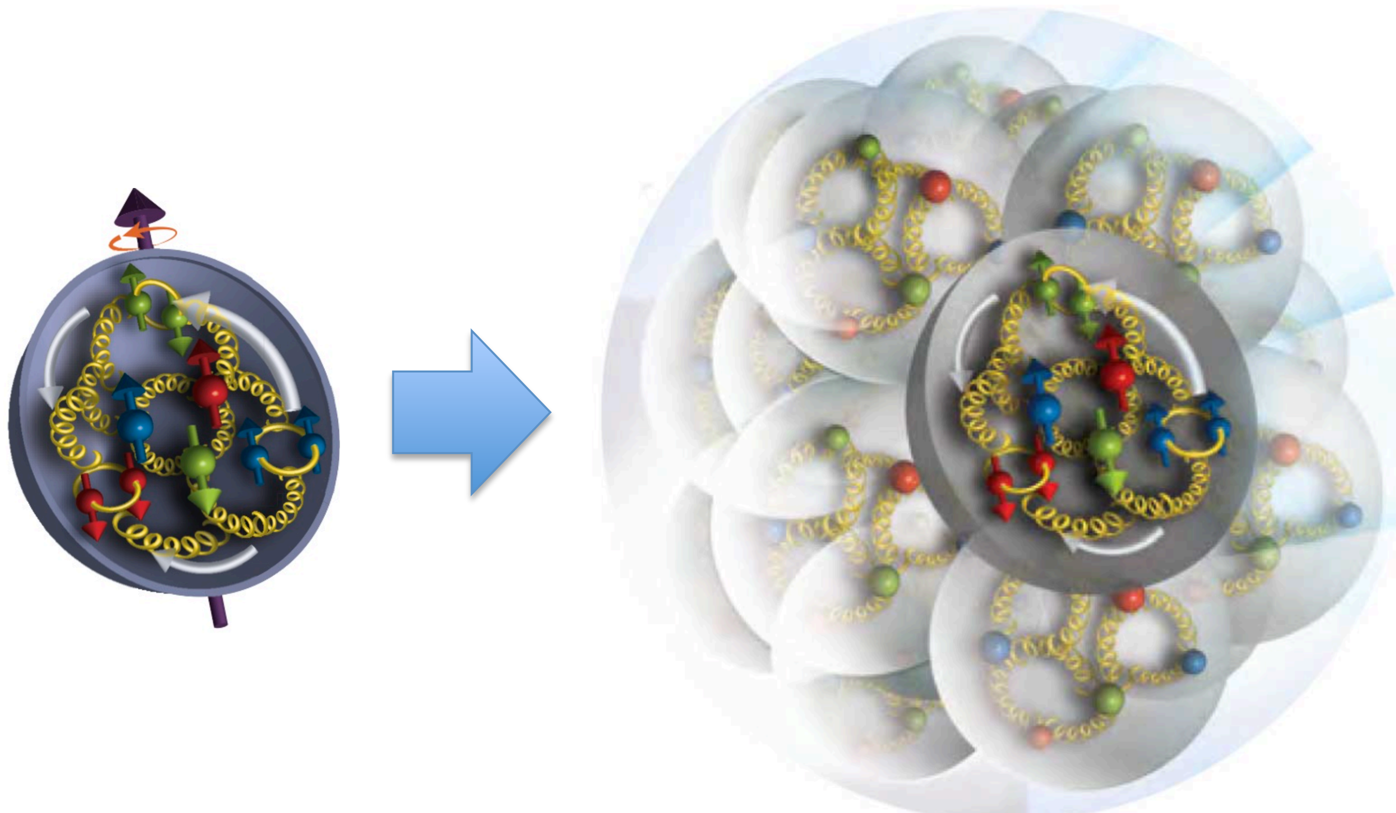
This edge determined by proton beam energy:
E_{proton} < 100 GeV -> $E_{electron}$ = 10 GeV^2

Measure at x of 10^{-3} to 1, exclusive processes
Luminosity: x 10 to 100 that of HERA

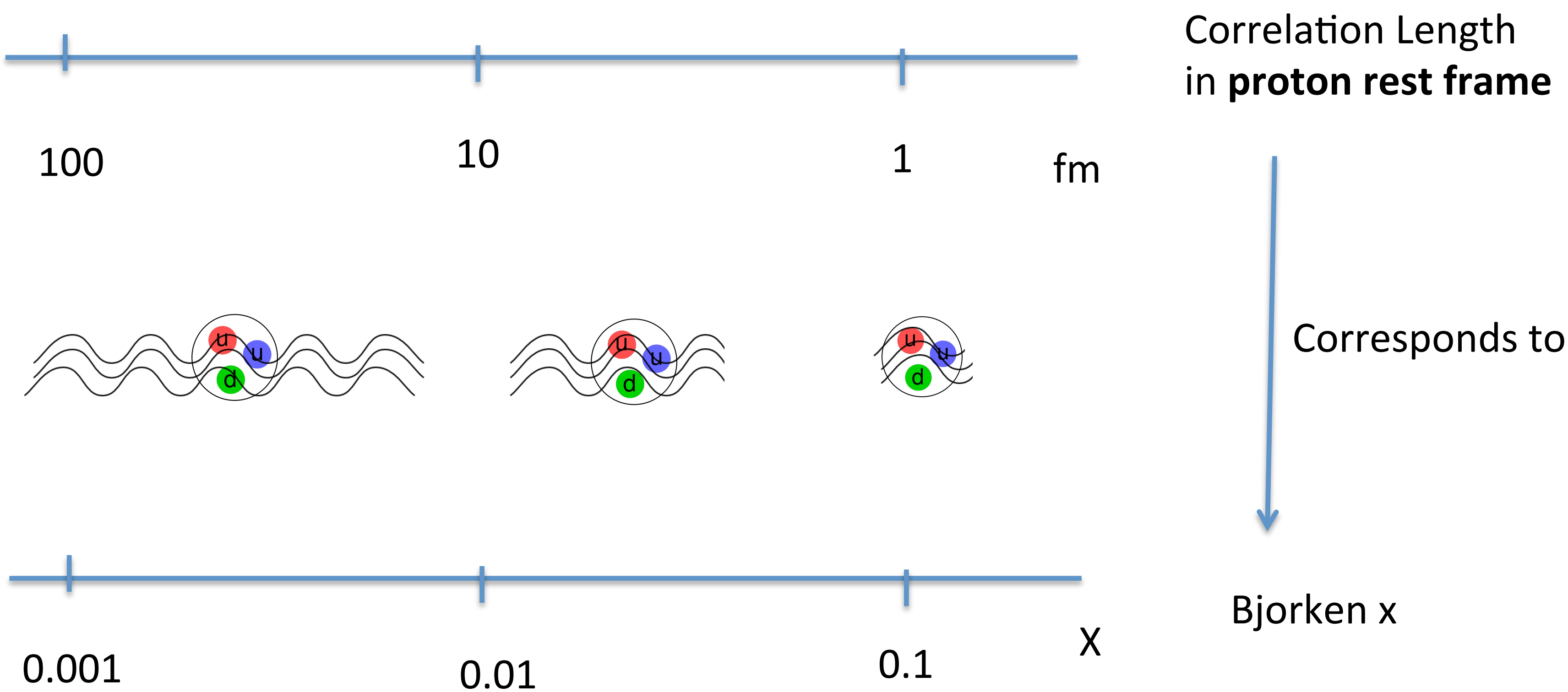
Understanding hadron structure cannot be done without understanding spin:
Polarized proton and electron beams

Sets some of the basic parameters of the JLEIC design

Understanding the nuclei at the next level

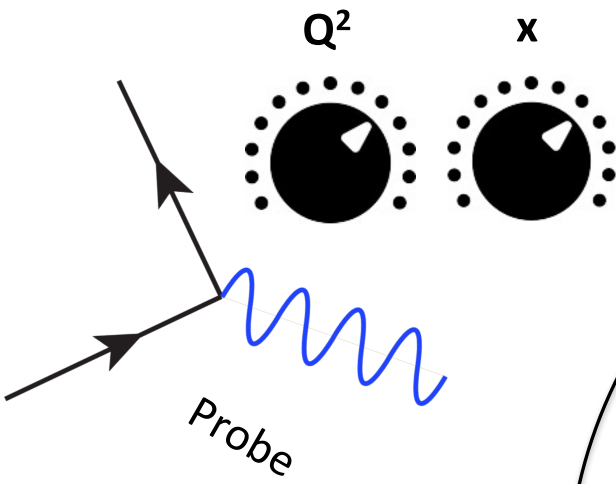


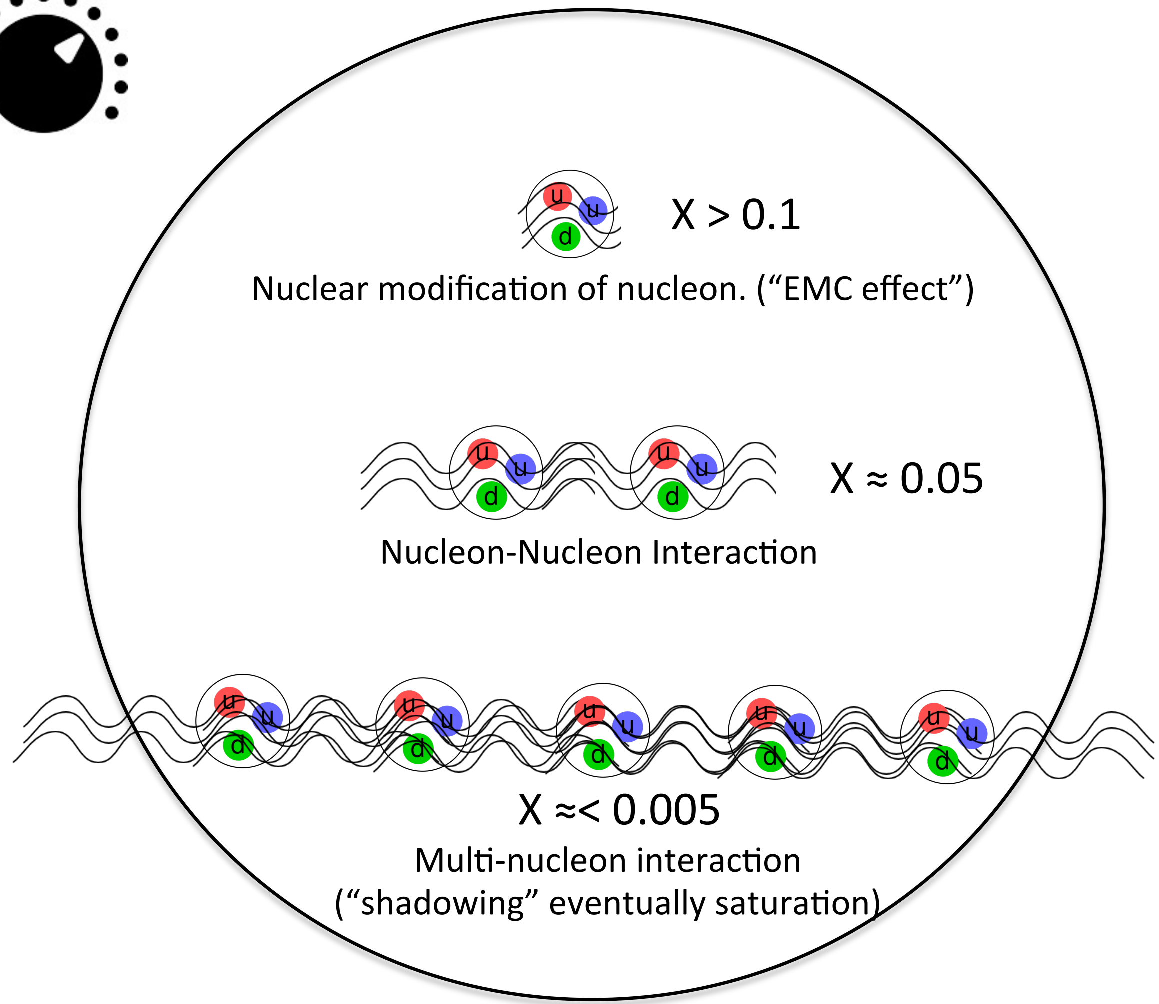
Bjorken x and length scale



In the proton rest frame, QCD field ($x < 0.1$) extends far beyond the proton charge radius

Parameters of the probe (nuclei)

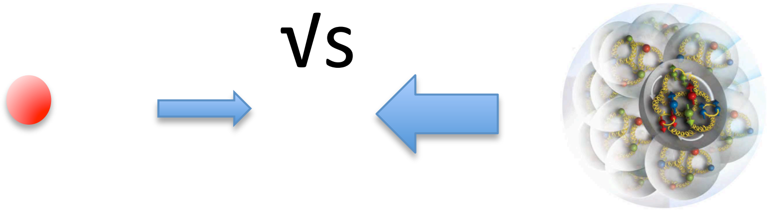


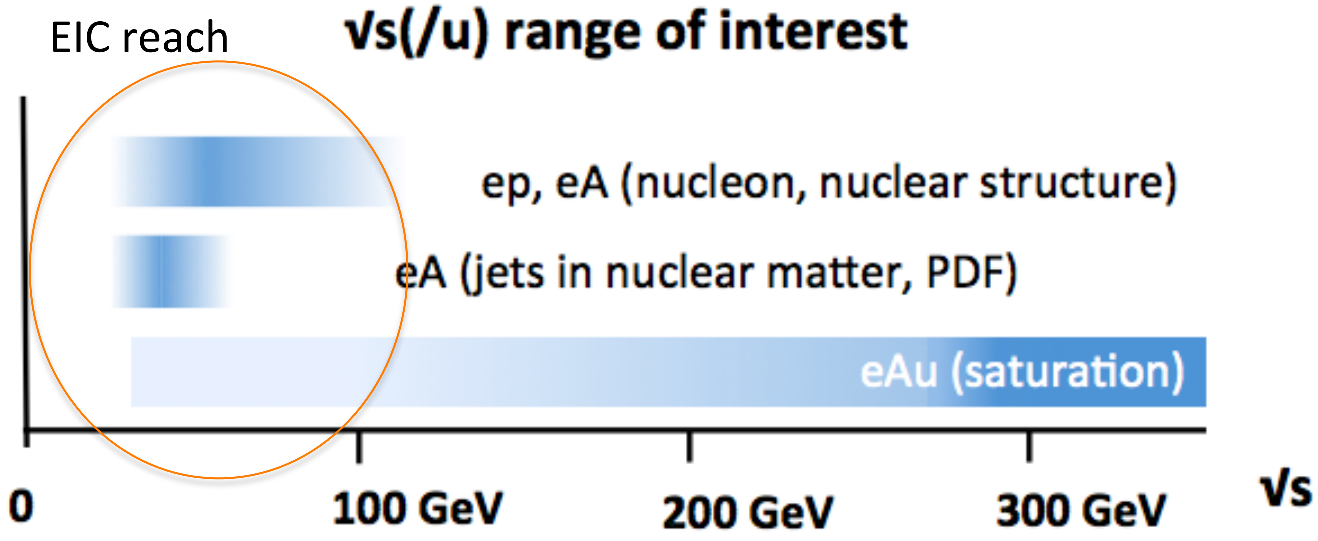


Probing the nucleon interaction in the nuclei (note this is different from correlation measurements)

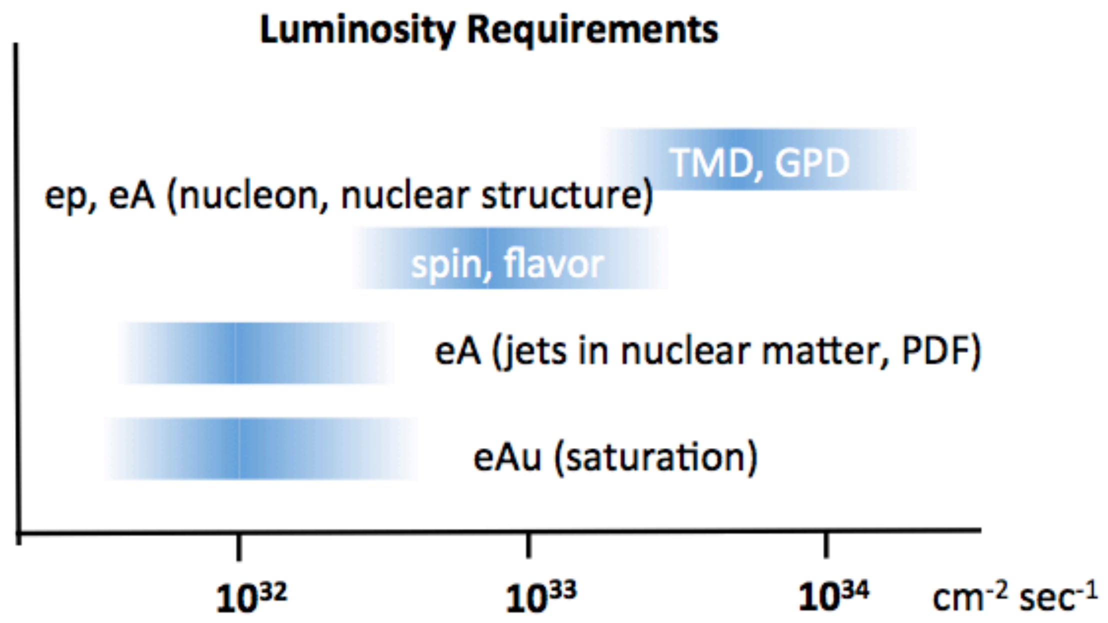
Designing the right probe: √s

What are the right parameters for the collider for the EIC science program?





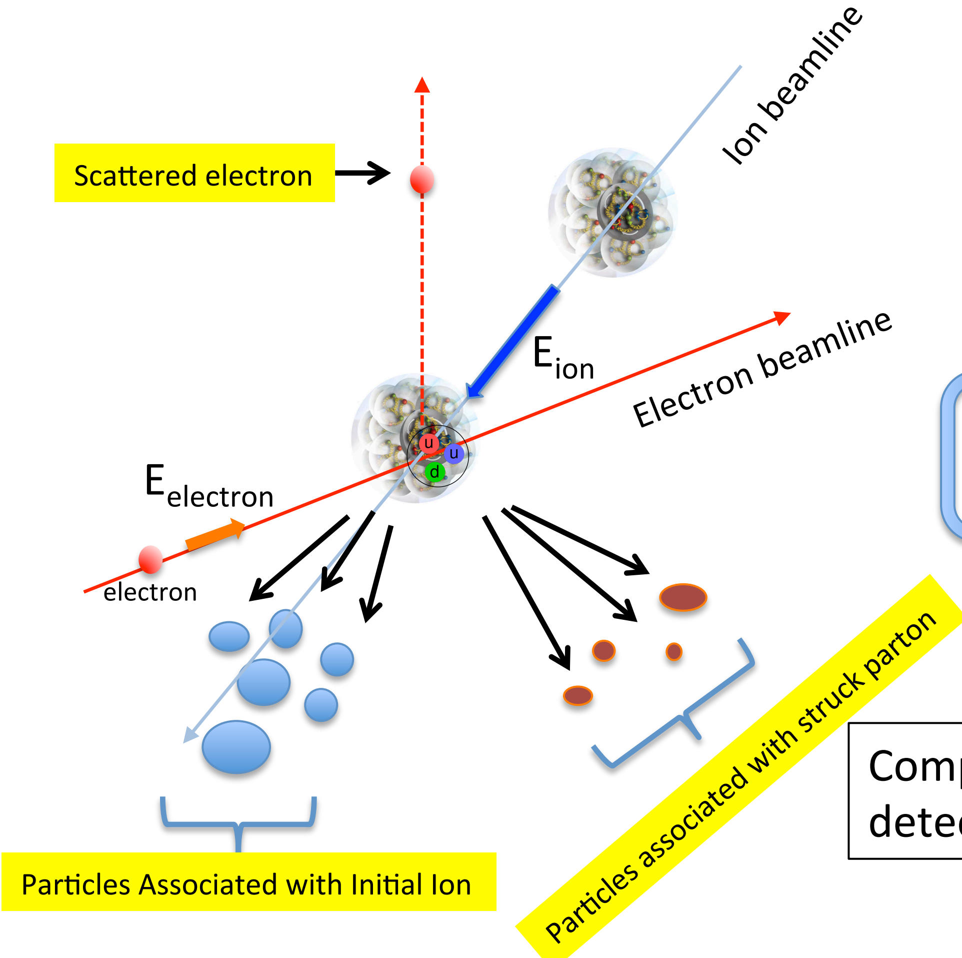
Luminosity needed for topics



Central mission of EIC (nuclear and nucleon structure) requires high luminosity.

We need to design a EIC physics program: including how and when to upgrade the machine

E_{ion} and $E_{ion}/E_{electron}$



EIC needs to detect all three types of particles

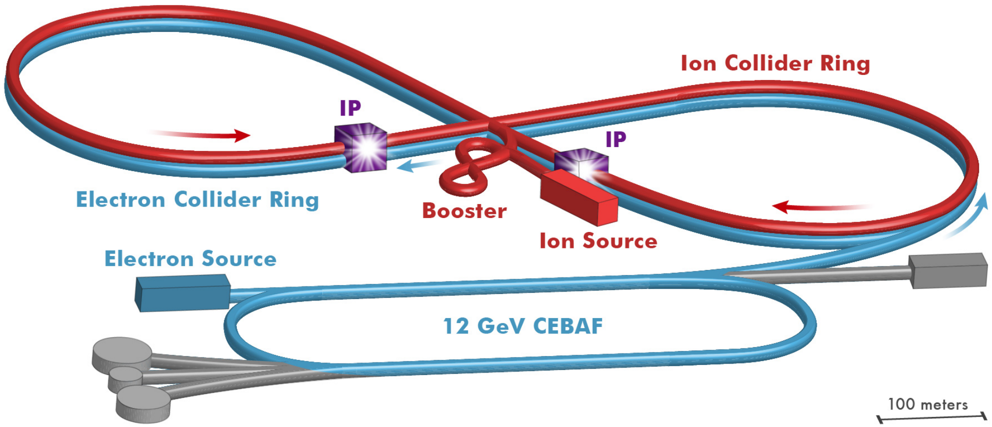
- Scattered electron
- Particles Associated with Initial Ion
- Particles associated with struck parton

These become more forward boosted and harder to measure with increasing E_{ion} and $E_{ion}/E_{electron}$

Complicated dependence on beam energies, detector capability and physics goals.

This optimization is on-going: E_{ion} <≈100 GeV and $E_{ion}/E_{electron}$ <≈10, current status → drives JLEIC baseline

JLEIC design strategy: High luminosity and polarization



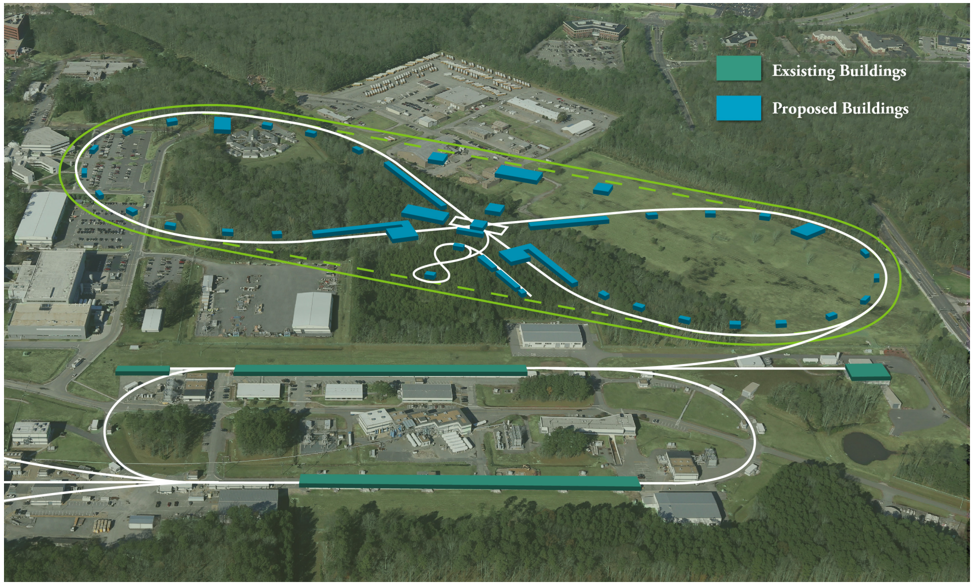


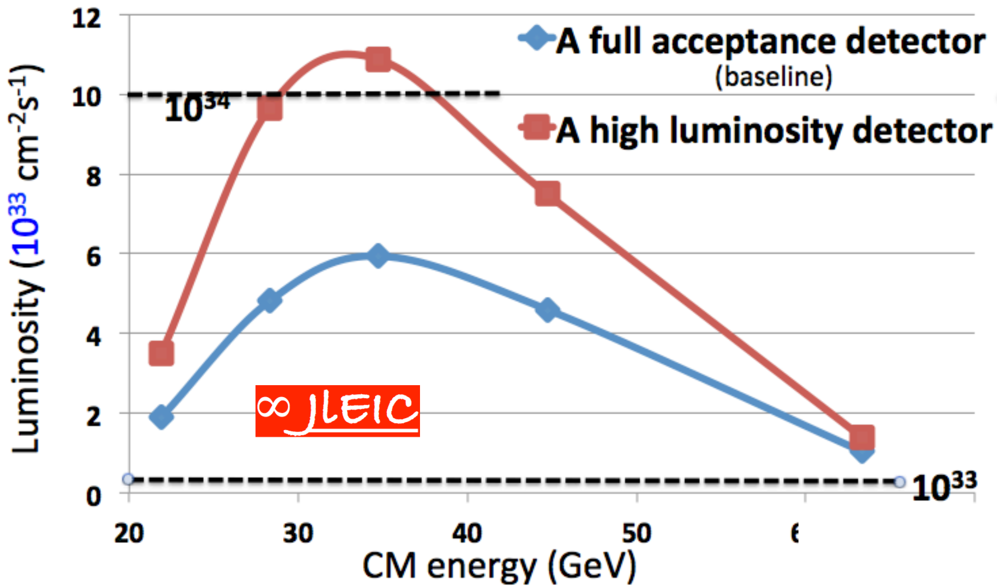
Figure-8 shaped ring-ring collider:

- **spin precessions** in left and right ring parts cancel exactly
- zero **spin tune** (net spin precession)
- energy-independent **spin tune**
- **polarization** easily preserved and manipulated:
  - by small solenoids
  - by other compact spin rotators

High luminosity:

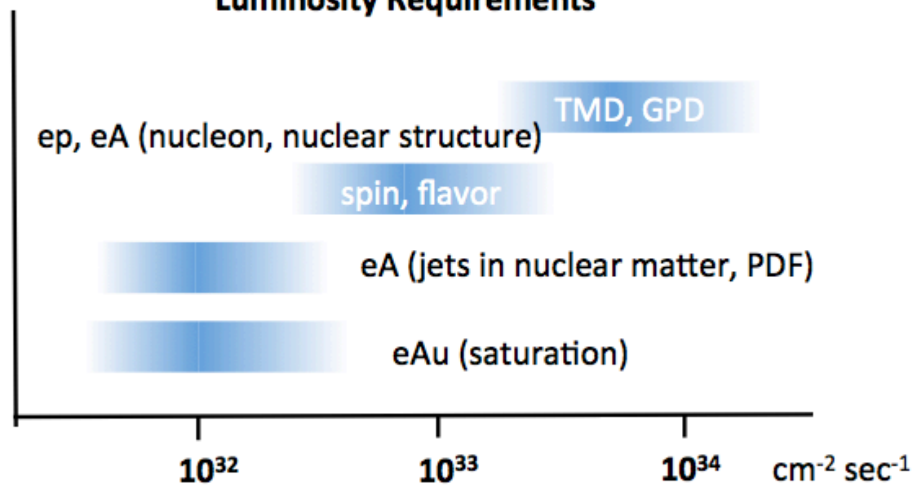
- high-rate collision of short bunches
  - with small emittance
  - with low charge
- **ion beam:** high-energy electron cooling (R&D)
- **electron beam:** synchrotron radiation damping

JLEIC luminosity reach



10^{34}

JLEIC baseline provides high luminosity needed to carry out the EIC physic program

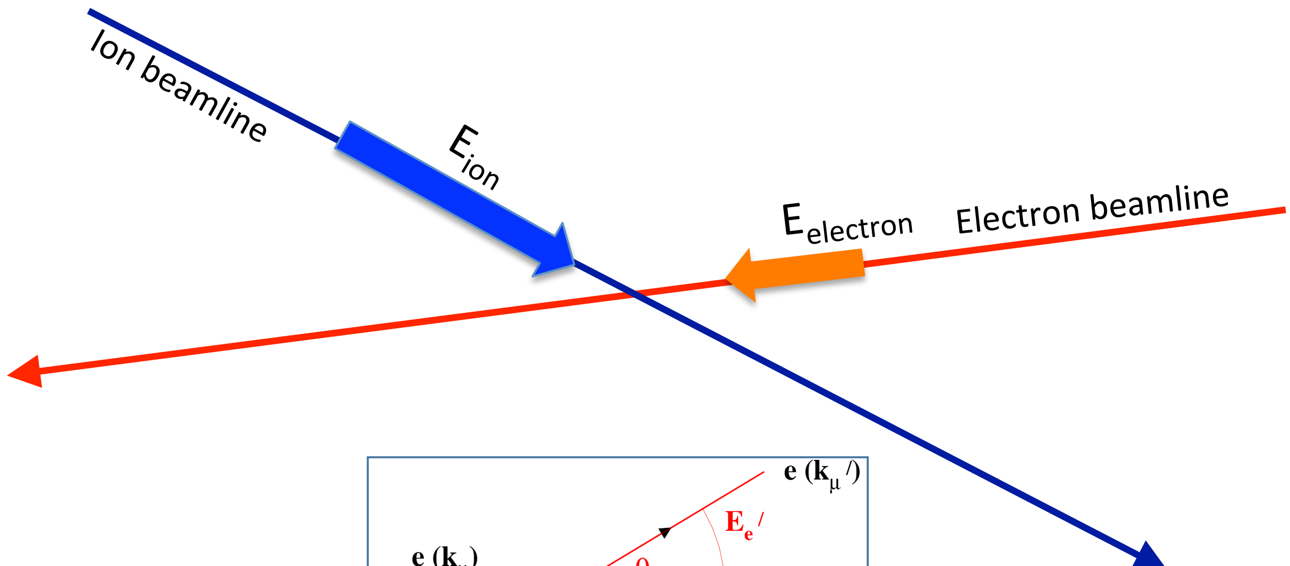


Section

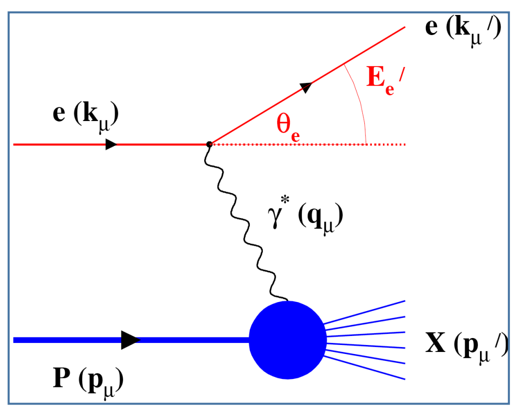
Detector Design – General design considerations

DIS and final-state particles

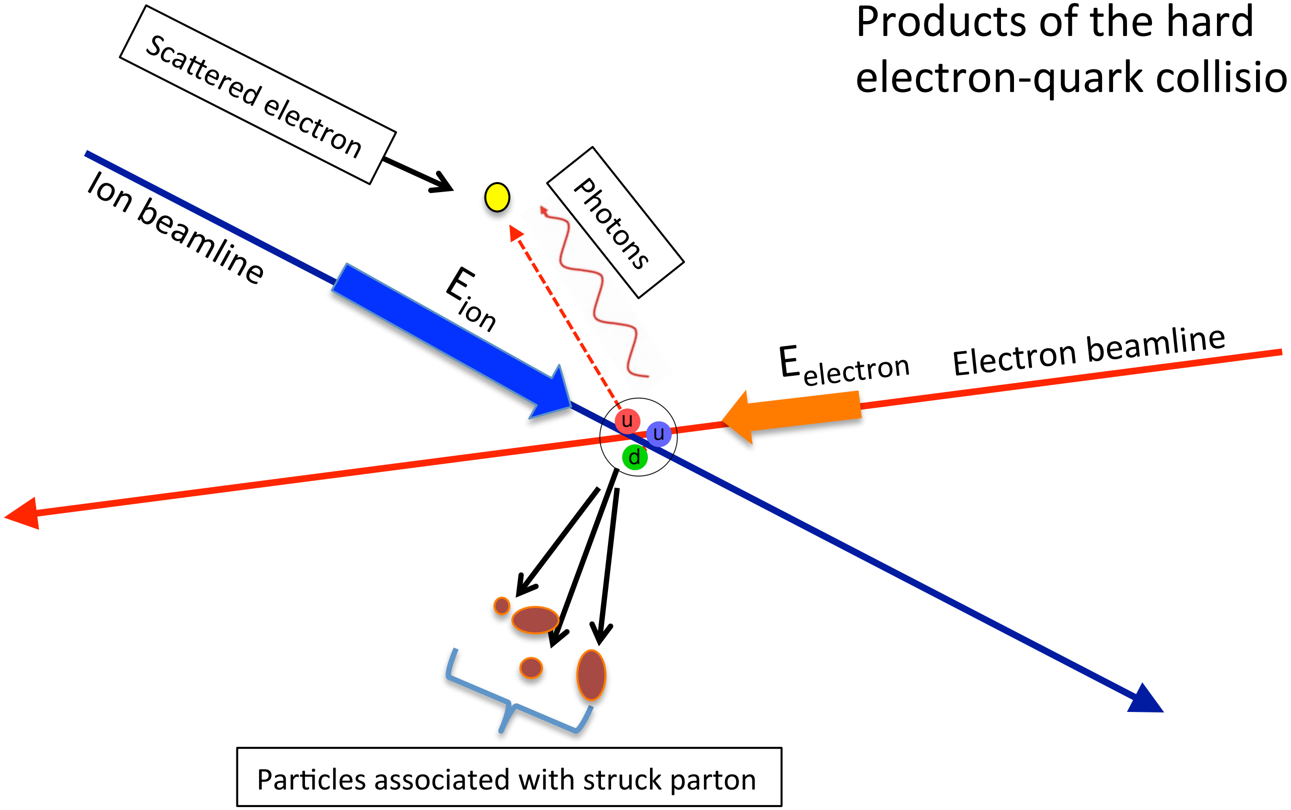
Aim of EIC is nucleon and nuclear structure beyond the longitudinal description. This makes the requirements for the machine and detector different from all previous colliders **including HERA**.



Need more than this



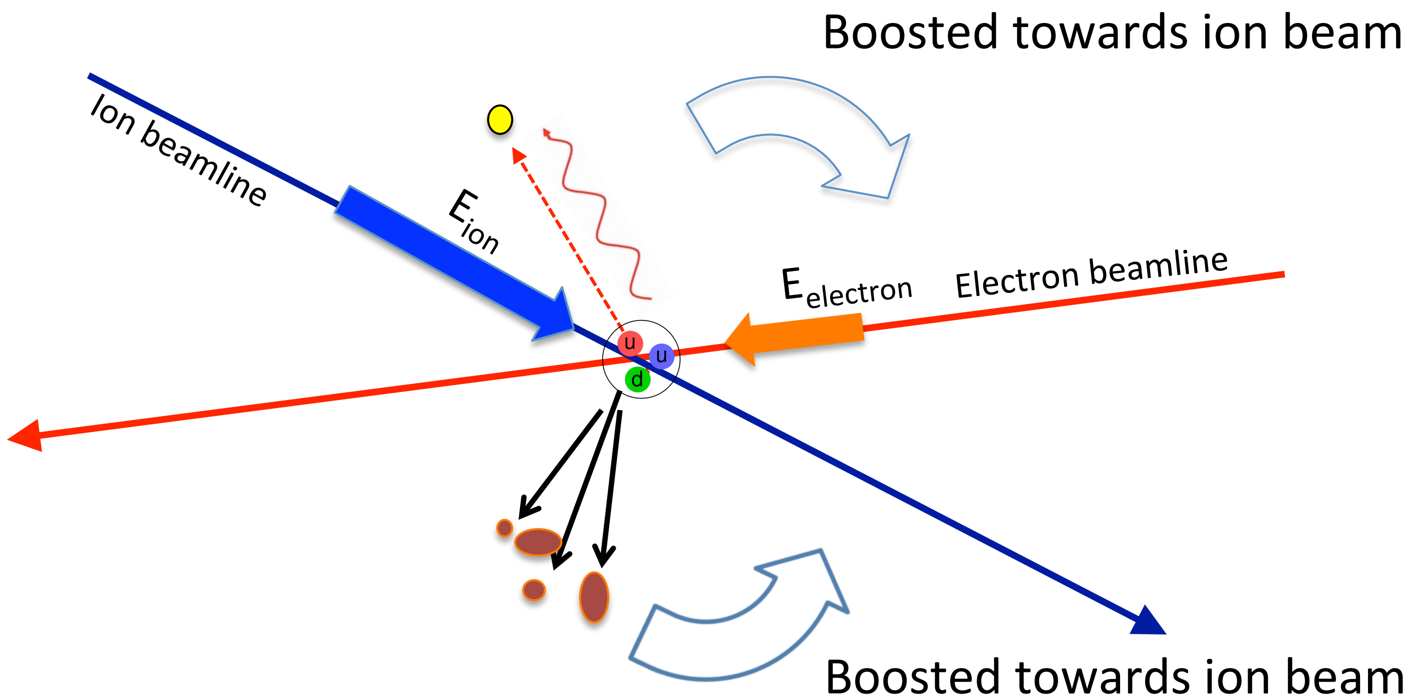
Final-state particles in the central rapidity



Products of the hard electron-quark collision

Transverse and flavor structure measurement of the nucleon and nuclei: The particles associated with struck parton must have its species identified and measured. **Particle ID much more important than at HERA**

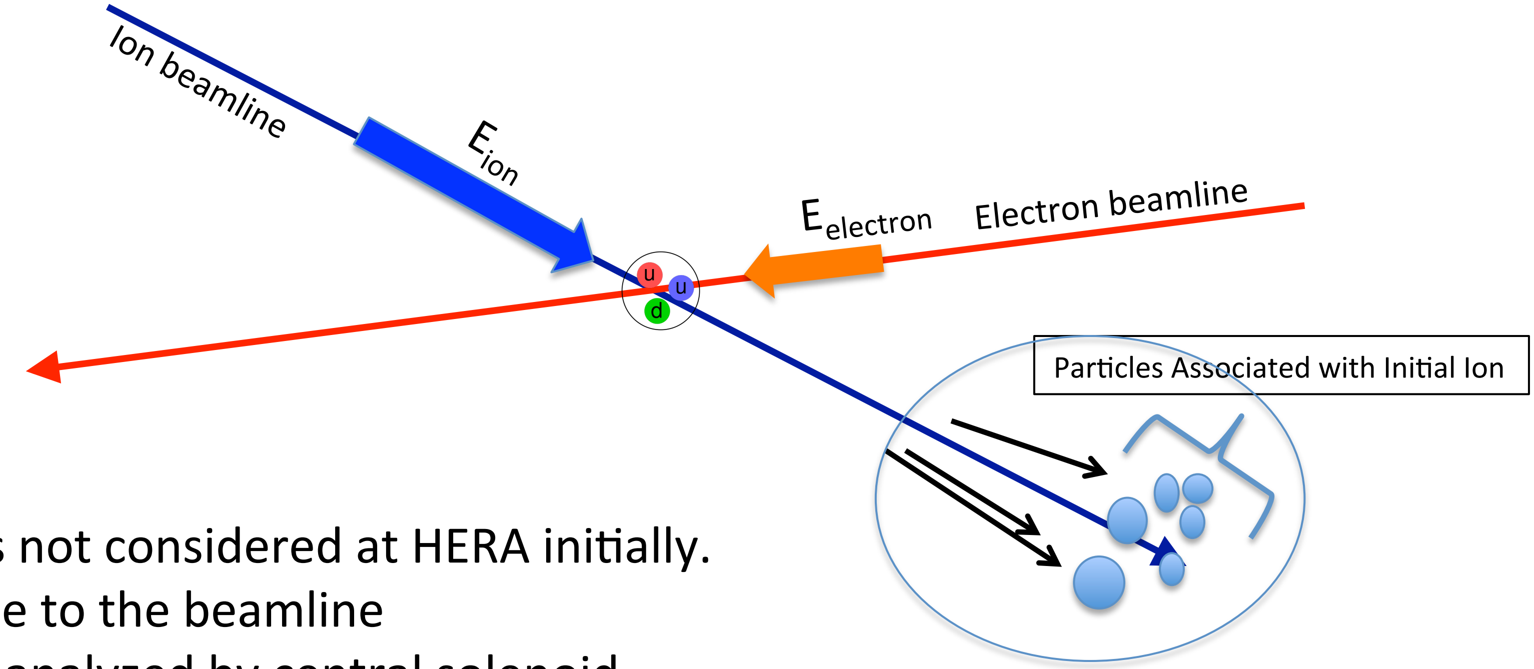
Final-state particles in the central rapidity



Asymmetric collision energies will boost the final state particles in the ion beam direction: **Detector requirements change as a function of rapidity**

Particles associated with the initial ion

For EIC, particles of the "target remnant" is as important as the struck parton



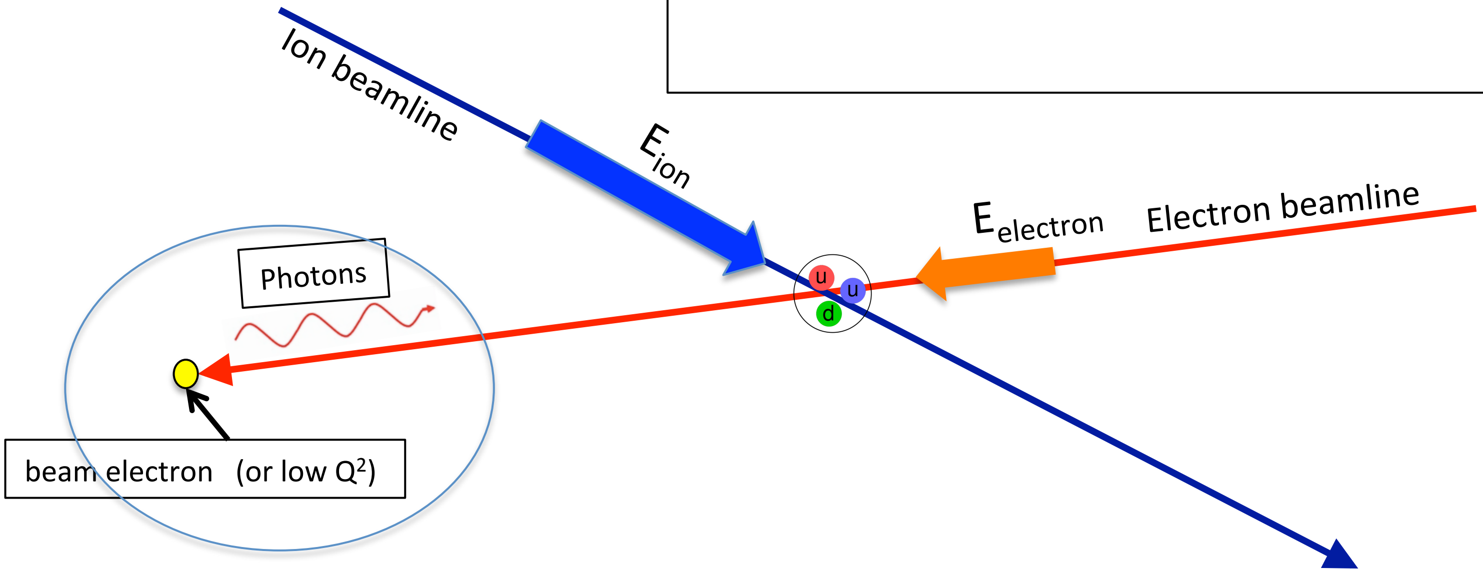
- Was not considered at HERA initially.
- Close to the beamline
- Not analyzed by central solenoid.
- **Aim for ~100% acceptance and good resolution at EIC.**

Remember acceptance is equally important as luminosity!

Particles associated with the initial electron

Forward Electron area:

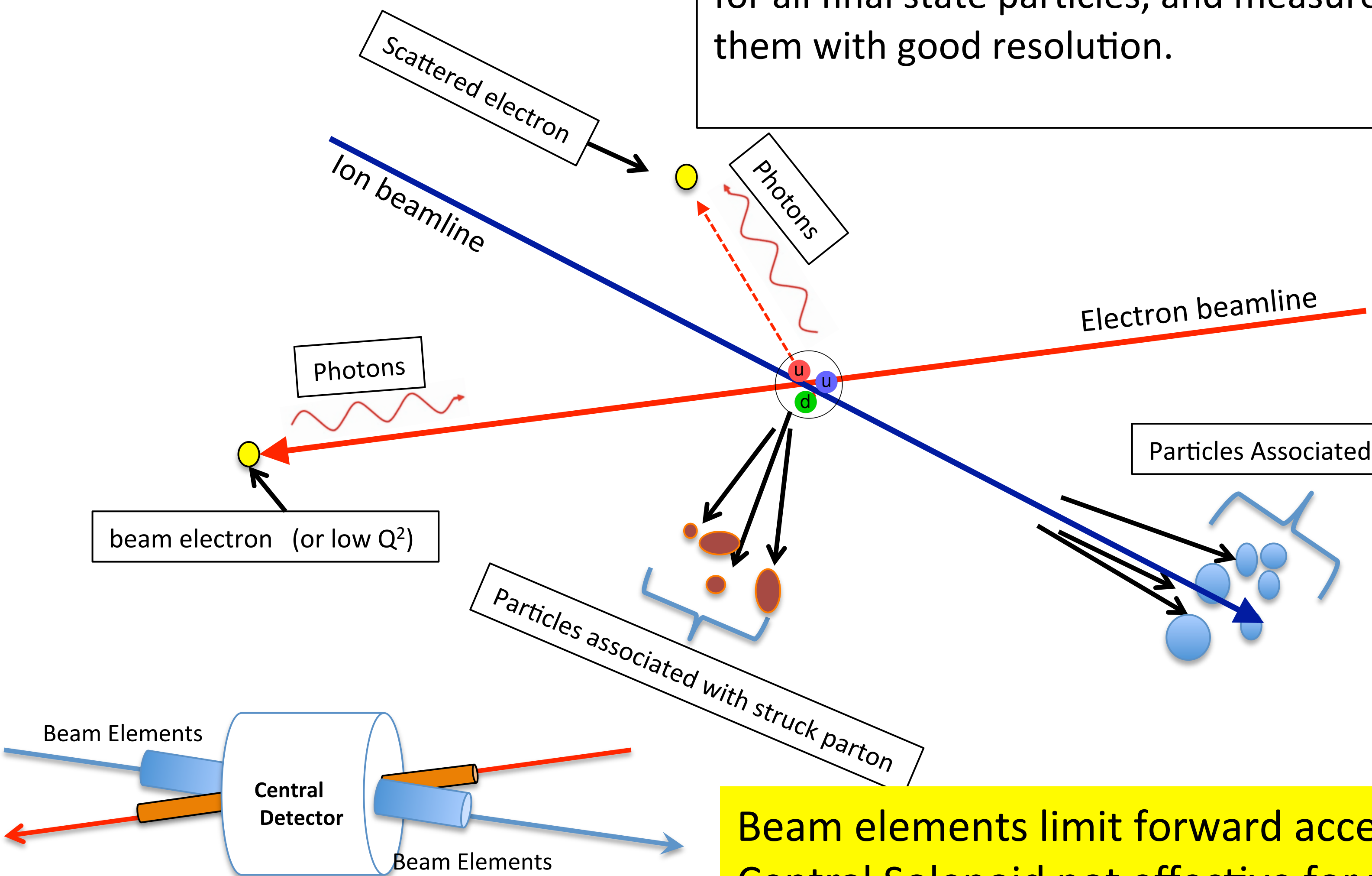
- Tag photoproduction ($Q^2 \approx 0$)
- Measure Luminosity
- Measure electron polarization



Apply lessons from HERA, JLab and elsewhere

Final-state particles

The aim is to get ~100% acceptance for all final state particles, and measure them with good resolution.

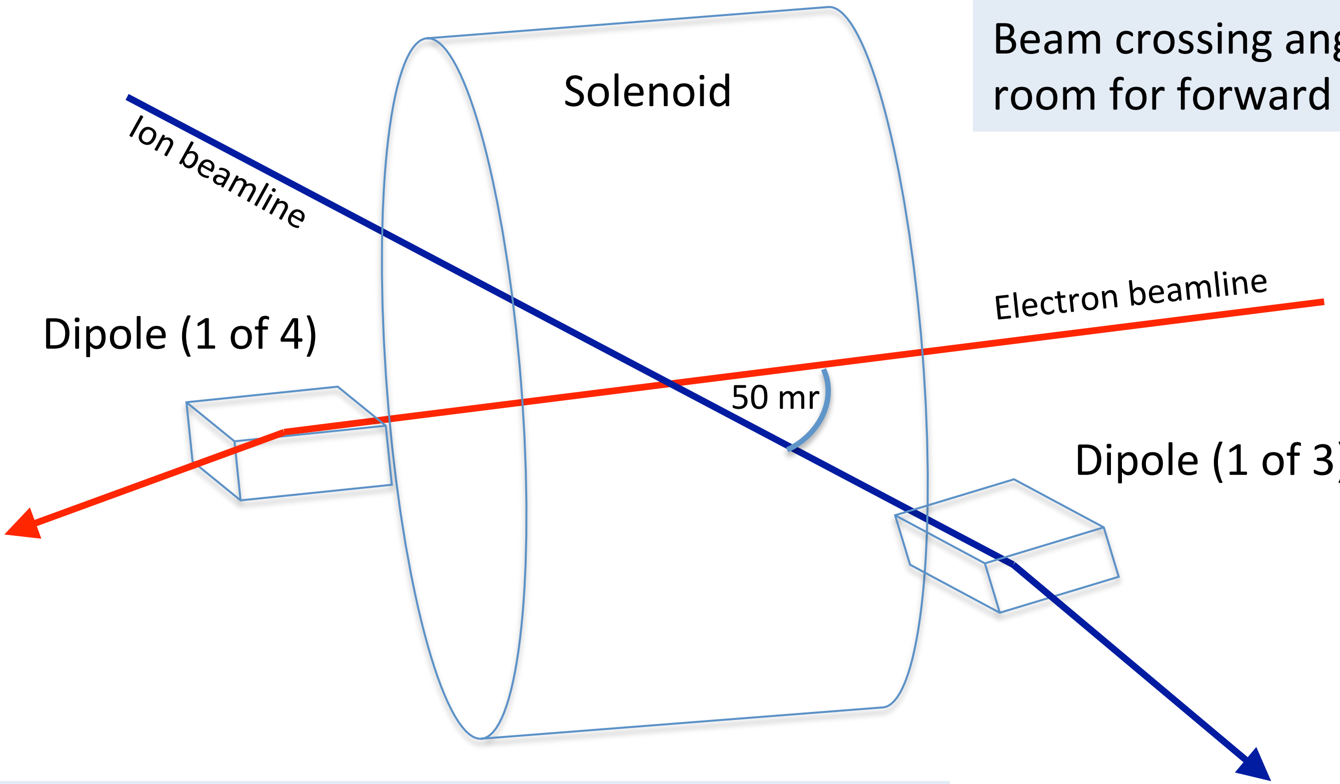


Beam elements limit forward acceptance
Central Solenoid not effective for forward

Interaction region concept

NOT TO SCALE!

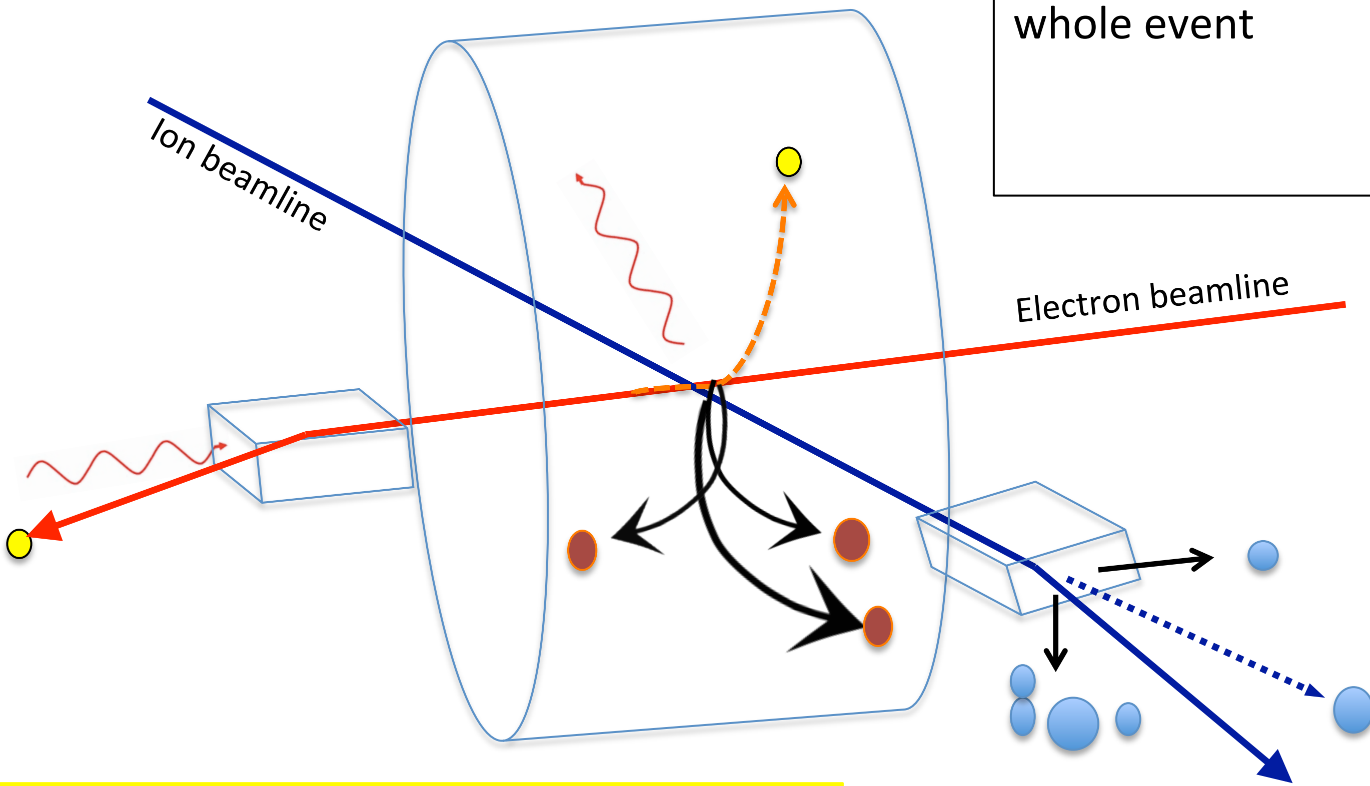
Beam crossing angle creates room for forward dipoles



Dipoles analyze the forward particles
and create space for detectors in the forward direction

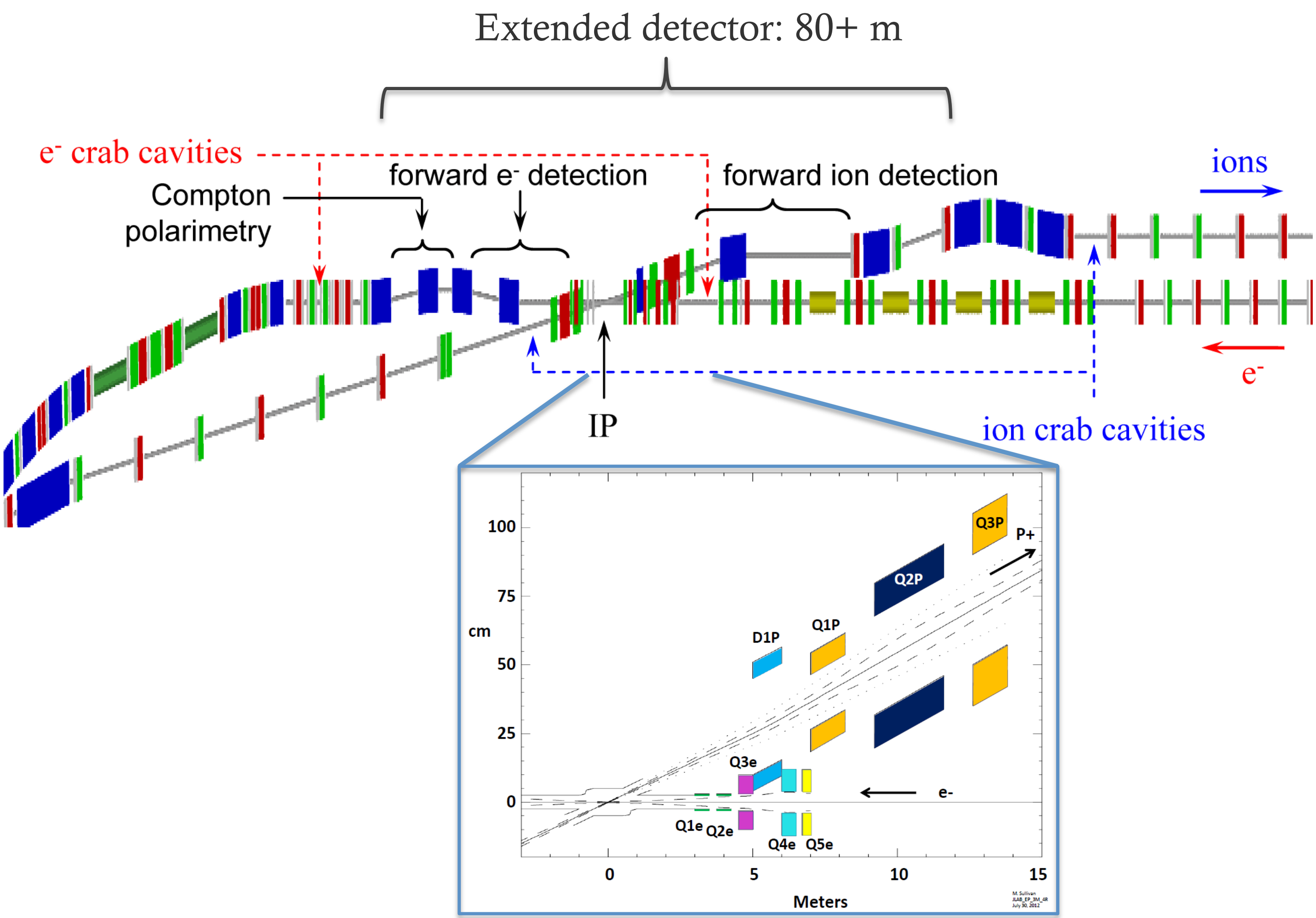
Interaction region concept

Possible to get ~100% acceptance for the whole event



Total acceptance detector (and IR)

JLEIC IR layout



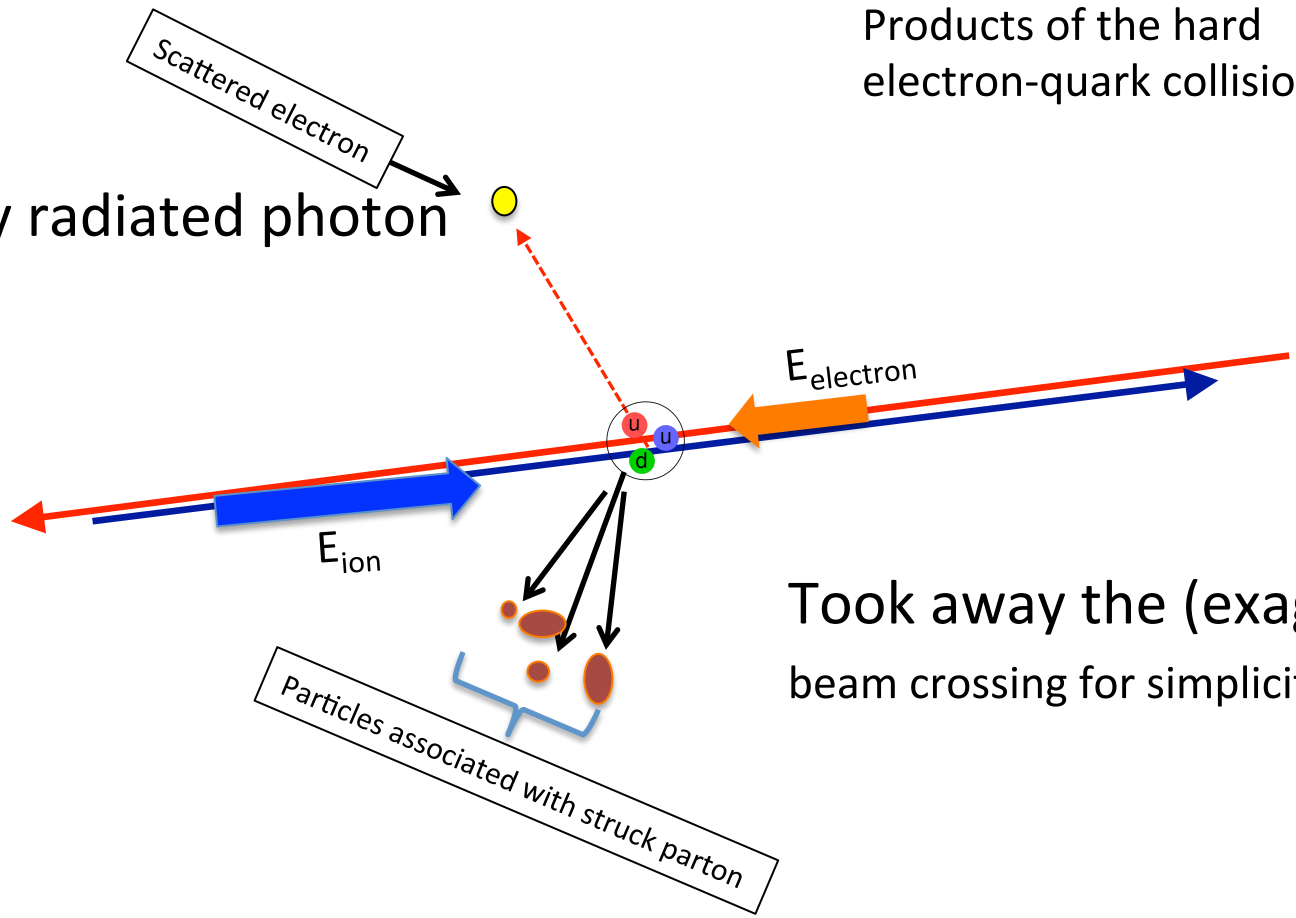
Section

Central Detector

Final-state particles in the Central Detector

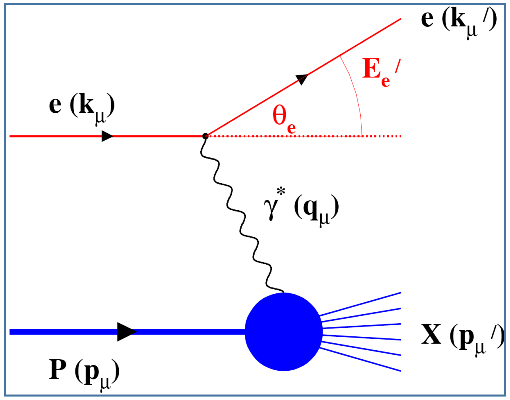
Products of the hard electron-quark collision

Took away radiated photon
for simplicity



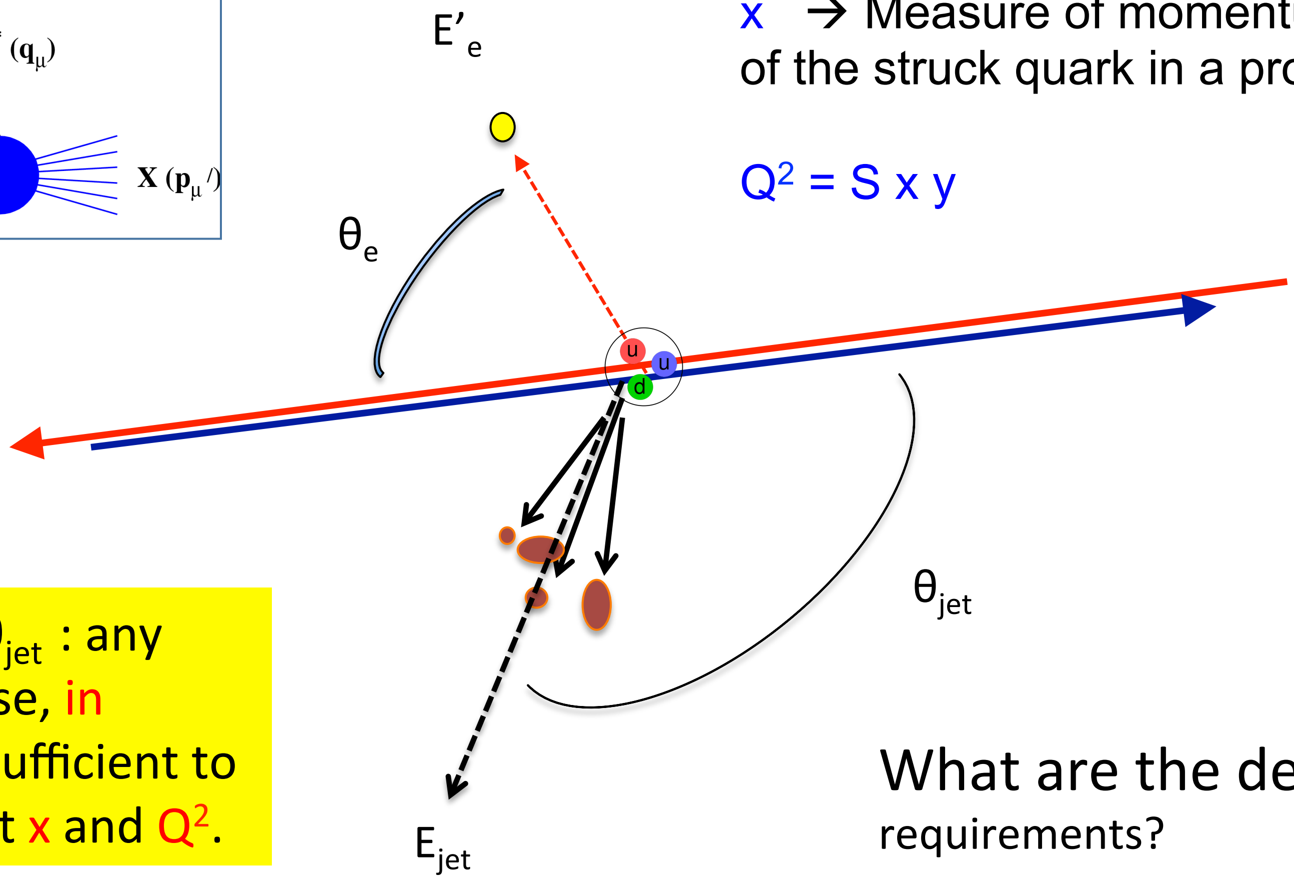
Took away the (exaggerated)
beam crossing for simplicity

Basic kinematic reconstruction



Q^2 → Measure of resolution
y → Measure of inelasticity
x → Measure of momentum fraction of the struck quark in a proton

$Q^2 = S\,x\,y$

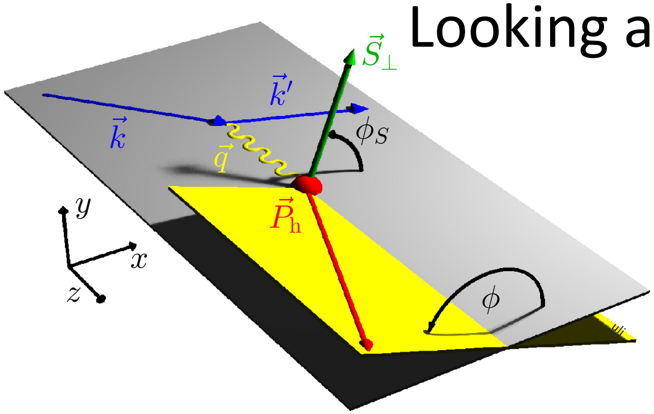


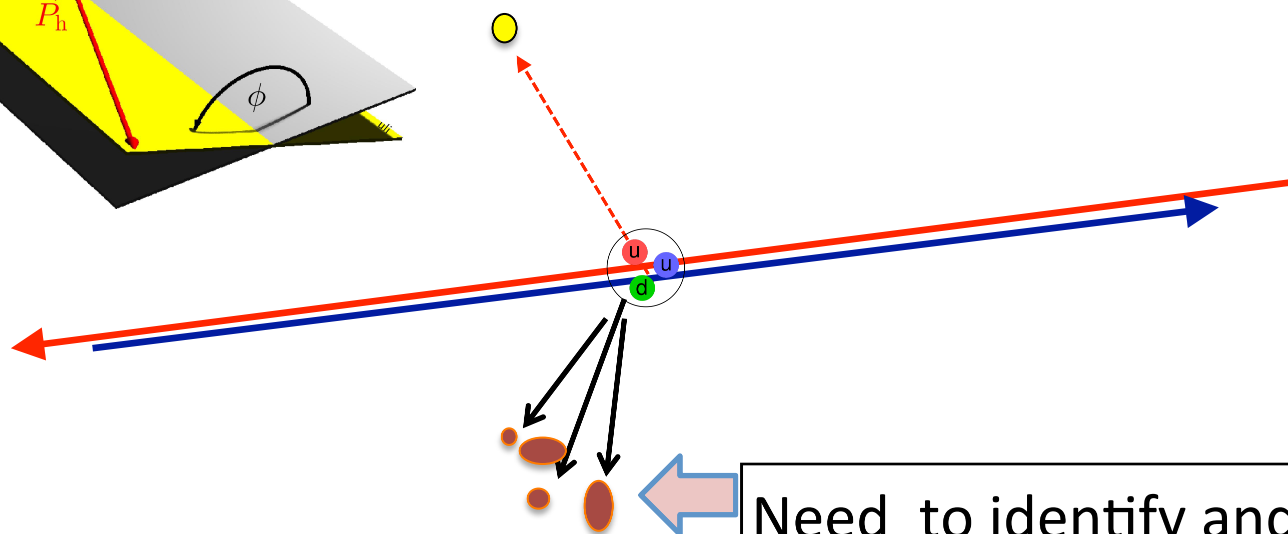
E'_e, θ_e, E_{jet}, θ_{jet} : any two of these, in principle, sufficient to reconstruct x and Q^2.

What are the detector requirements?

Reconstruction for transvers structure

Looking at out-of –plane component in the final state





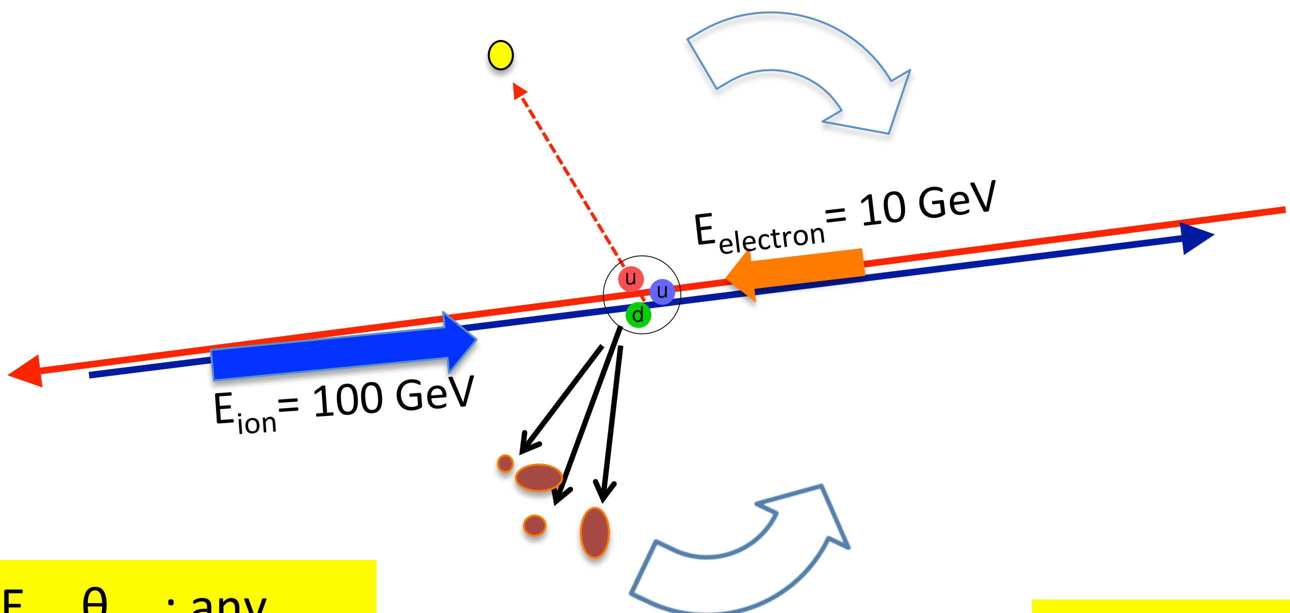
Need to identify and measure these particles

What are the detector requirements?

How boosted is the final state?

No Monte Carlo needed to Determine

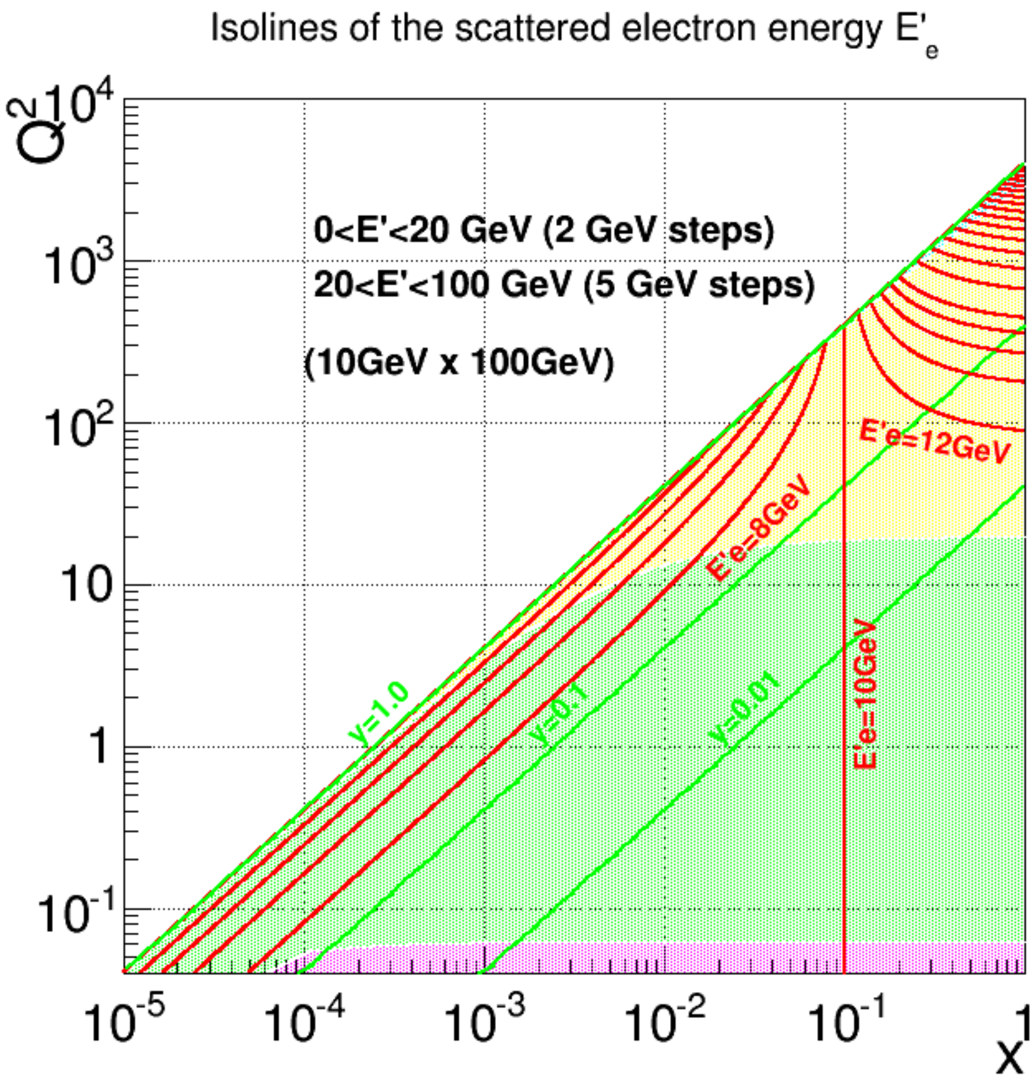
Boosted towards ion beam

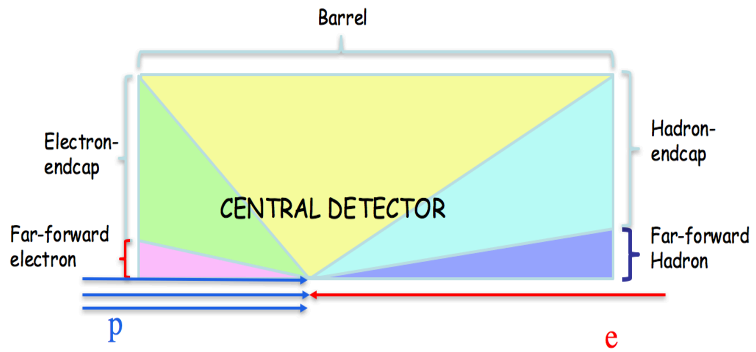


$E'_{e}, \theta_e, E_{jet}, \theta_{jet}$: any two of these, in principle, sufficient to reconstruct x and Q^2.

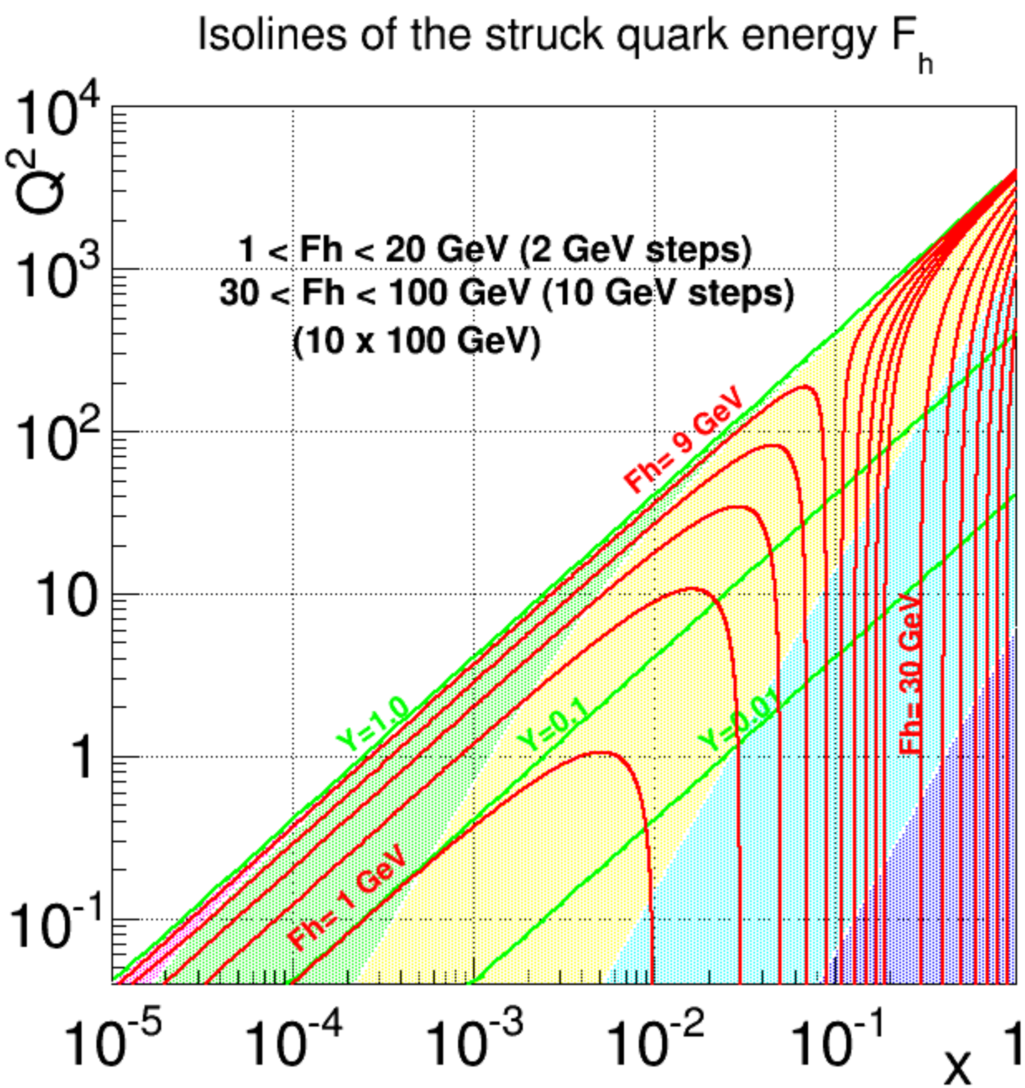
Given x and Q^2, **$E'_{e}, \theta_e, E_{jet}, \theta_{jet}$** are all fixed

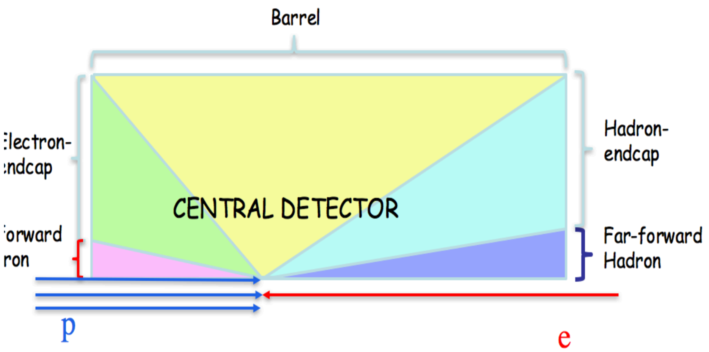
Electron isoline plot





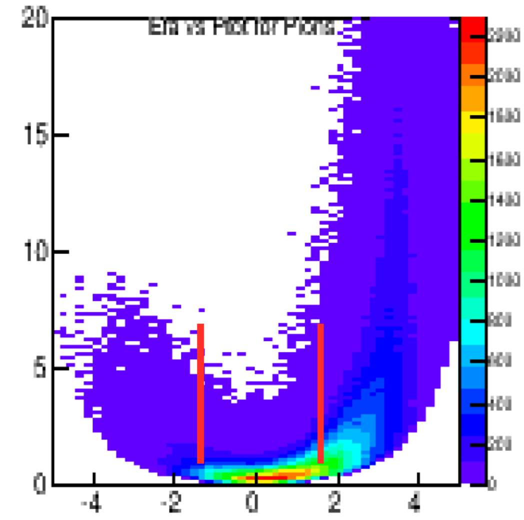
Quark (jet) isoline plot

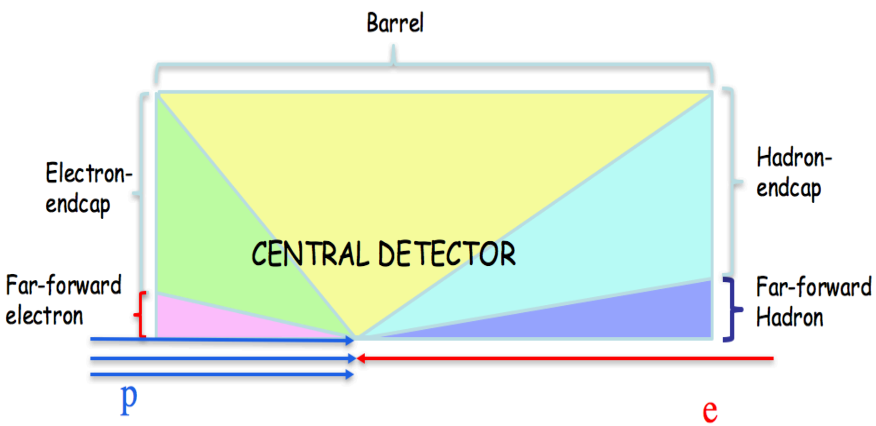




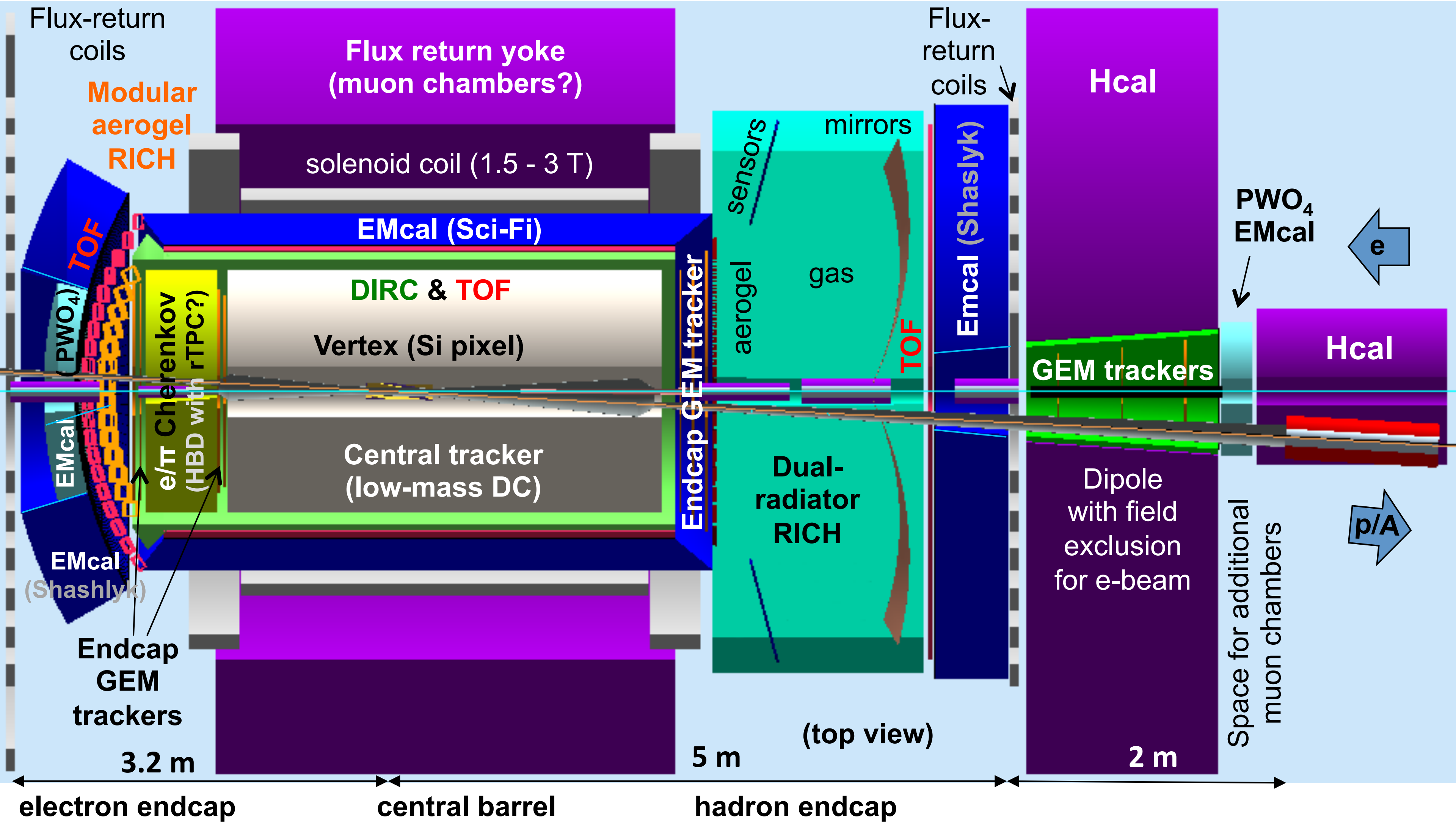
Particle distribution

	E-endcap	Barrel	H-endcap
E'e	<8GeV	8-50GeV	>50 GeV
Ejet	<10GeV	~10-50GeV	20-100GeV
E,hadrons	<10GeV	<15GeV	~15-50GeV
occupancy	low	medium	high





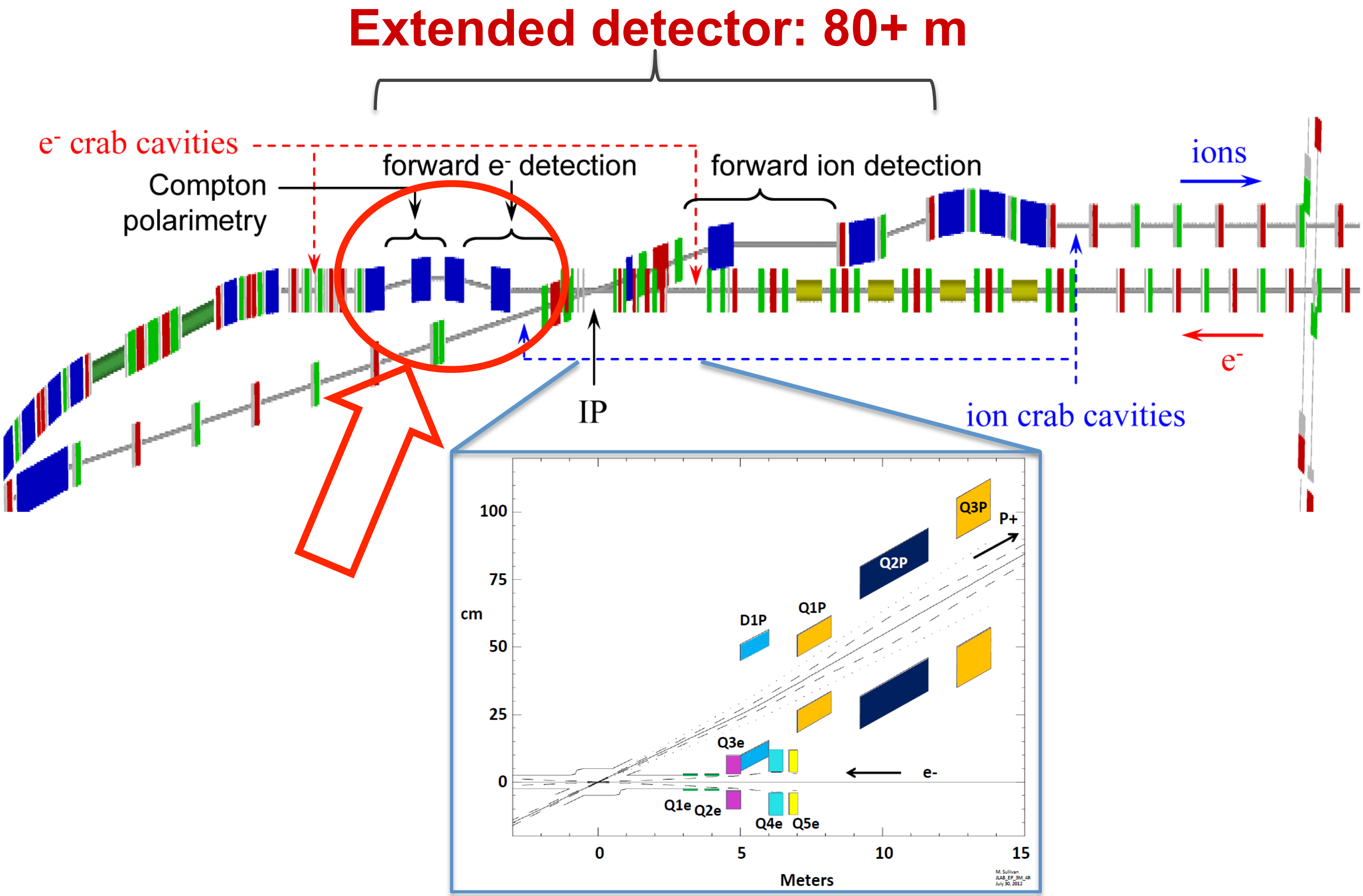
Central detector overview



Section

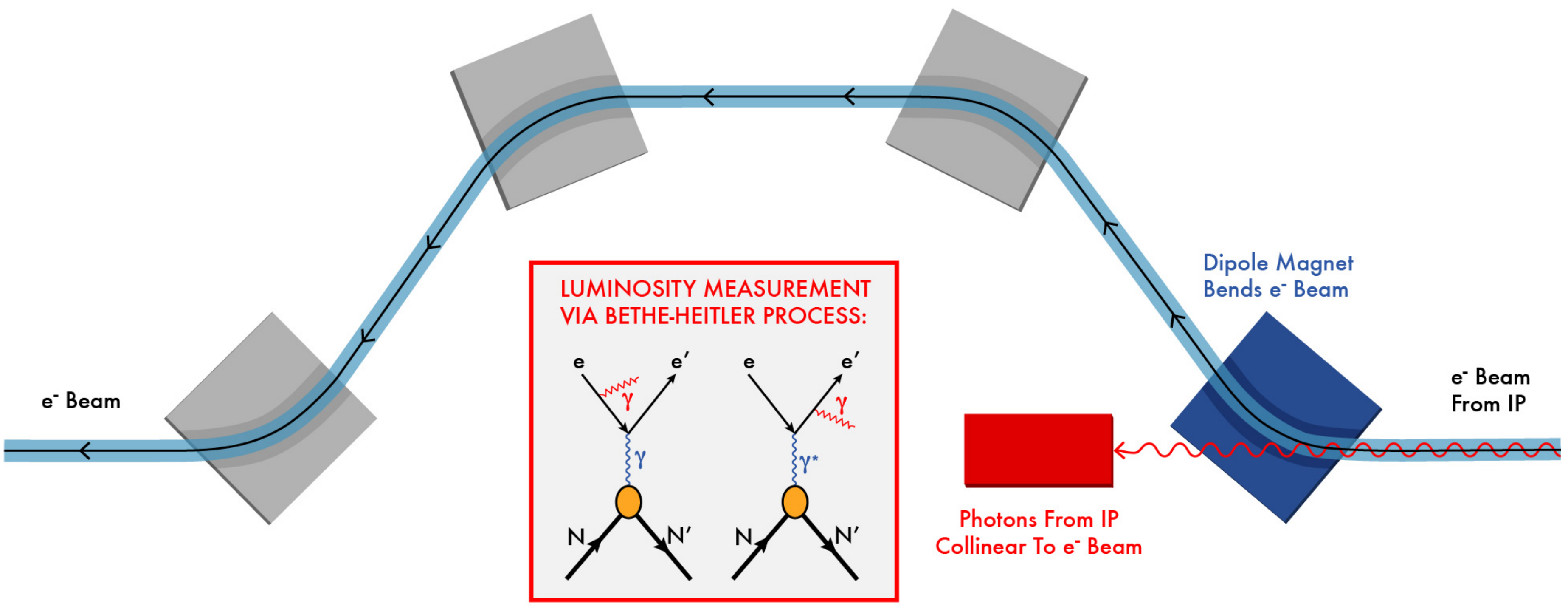
Detectors in electron-beam direction

Chicane for electron-forward detection

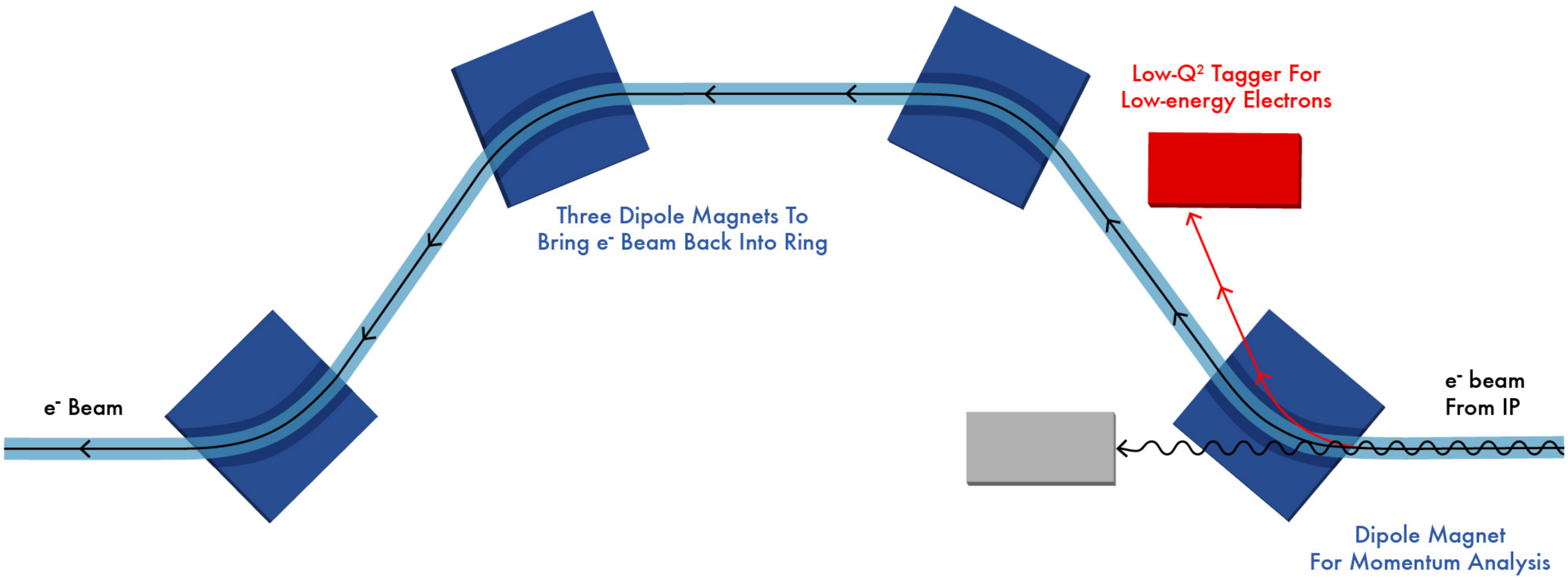


Luminosity measurement

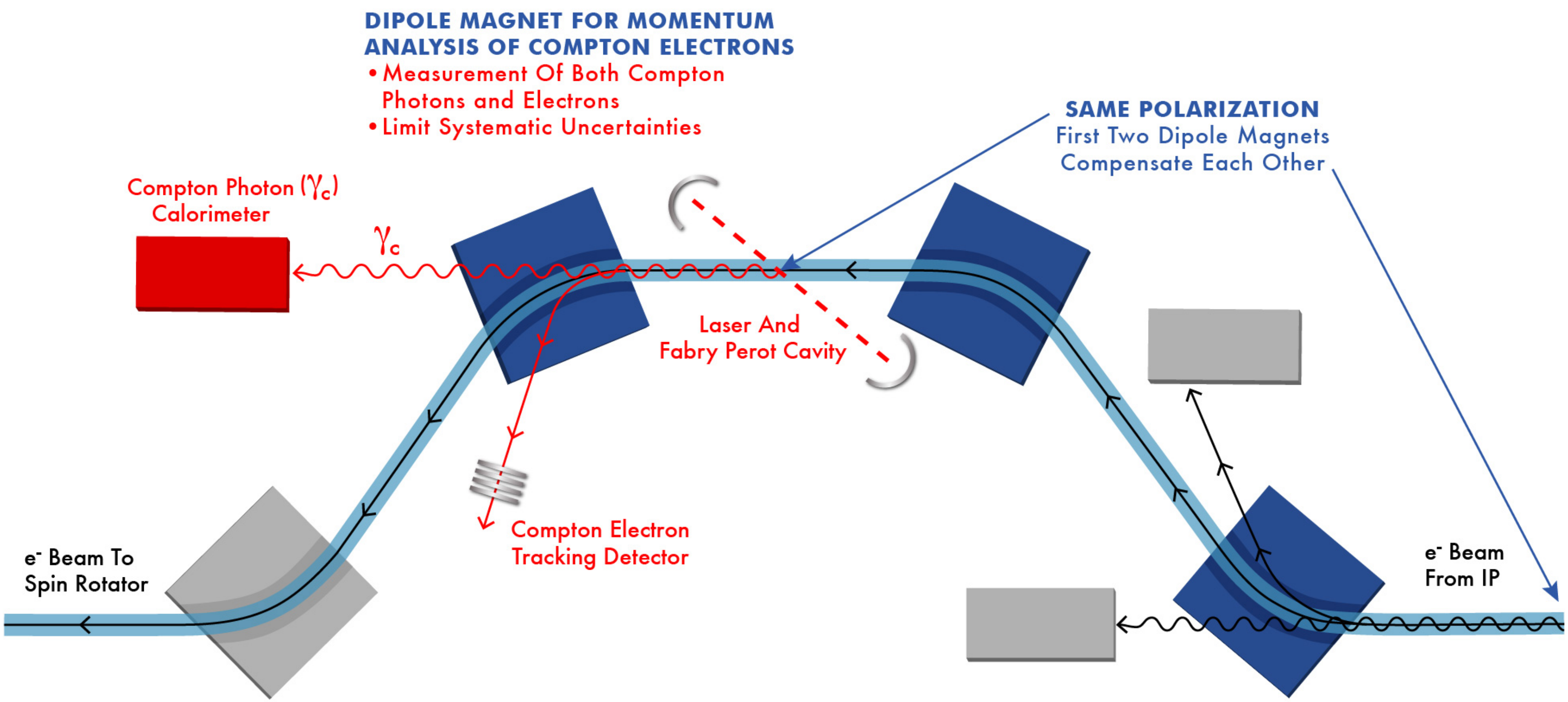
Use Bethe-Heitler process to monitor luminosity (same as HERA)



Low-Q^2 tagger

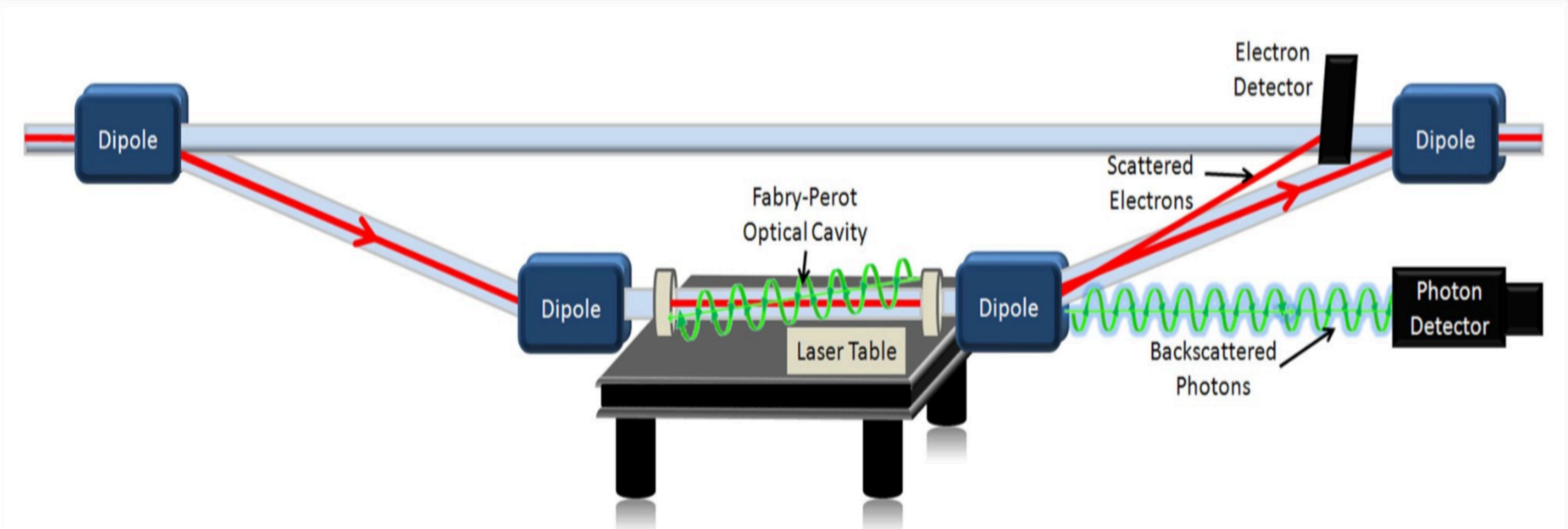


Polarization measurement



Note the off-momentum electrons from IP does not enter the luminosity Compton tracker.

Compton polarimetry

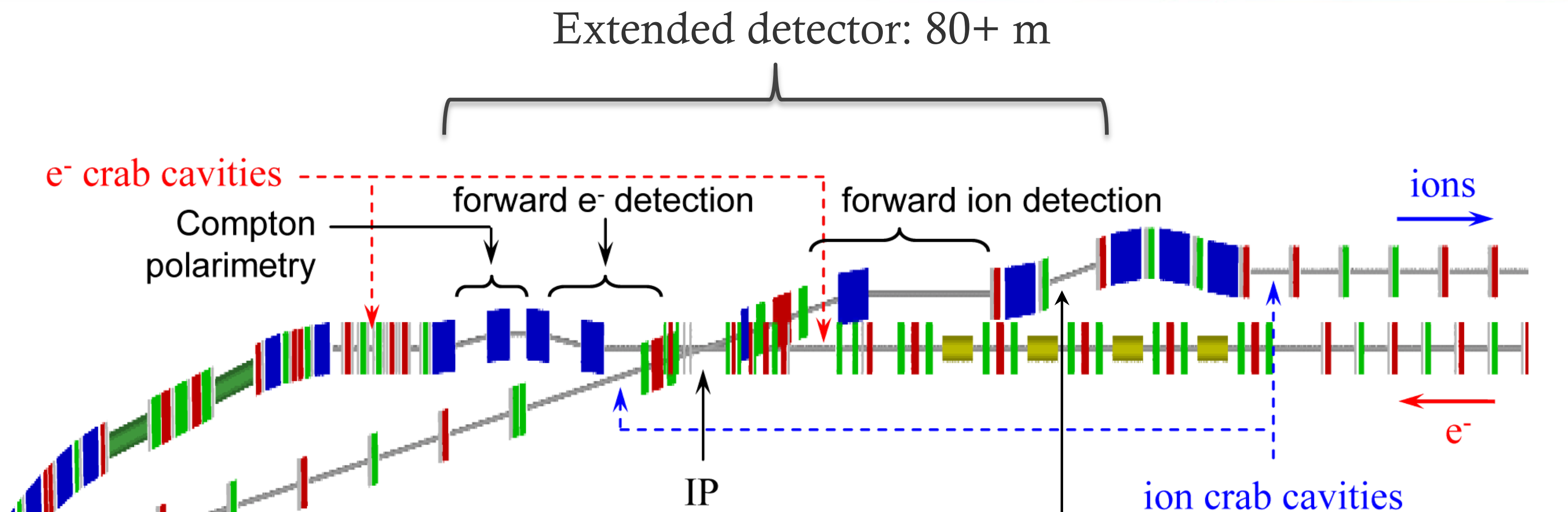


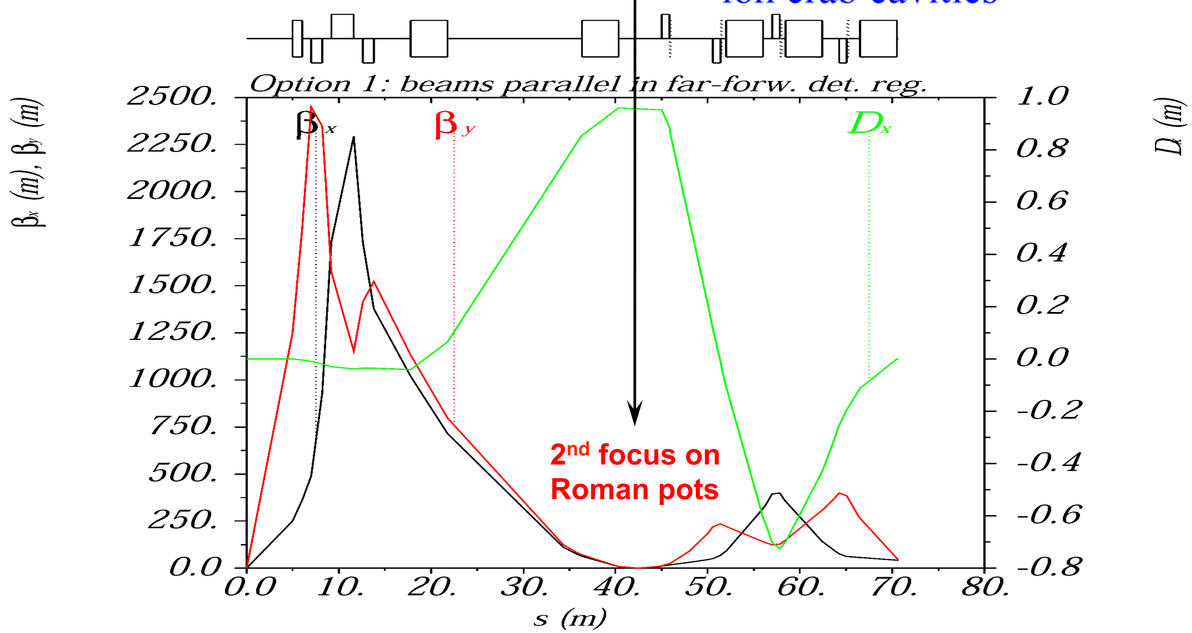
Existing Polarimeter in Hall C at JLab: Achieved 0.6% Precision

Section

Detectors in ion-beam direction

Ion optics for near-beam detection





- A large ***dispersion*** at the detection point separates scattered (off-momentum) particles from the beam.
- A ***second focus*** and small emittance (cooling) allows moving detectors closer to the beam

EIC forward detection requirements

- Good acceptance for recoil nucleons (rigidity close to beam)
  - **Diffractive processes on nucleon**, coherent nuclear reactions
  - Small beam size at detection point (to get close to the beam)

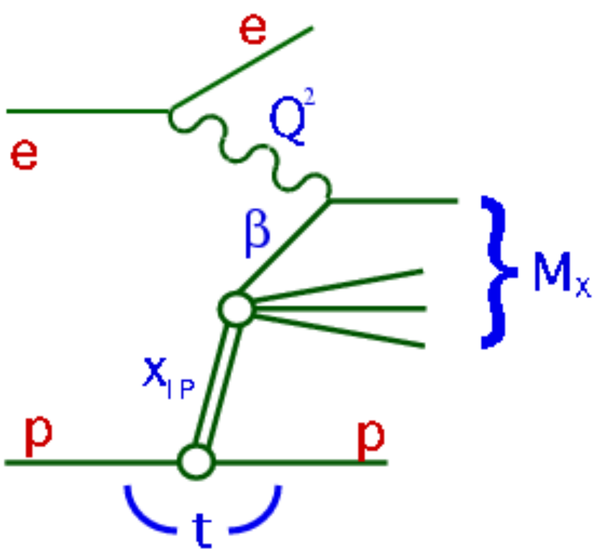
    Secondary focus on roman pots, small beam emmittance (cooling)
  - Large dispersion (to separate scattered particles from the beam)

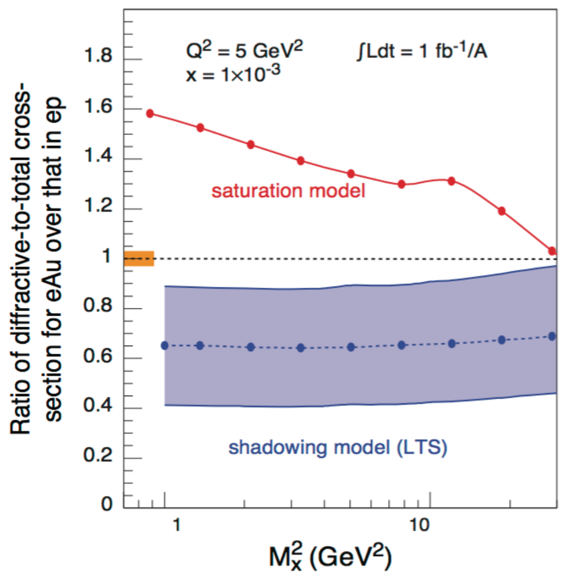
- Good acceptance for fragments (rigidity different than beam)
  - Tagging in light and heavy nuclei, nuclear diffraction
  - Large magnet apertures (low gradients)
  - Detection at several points along a long, aperture-free drift region

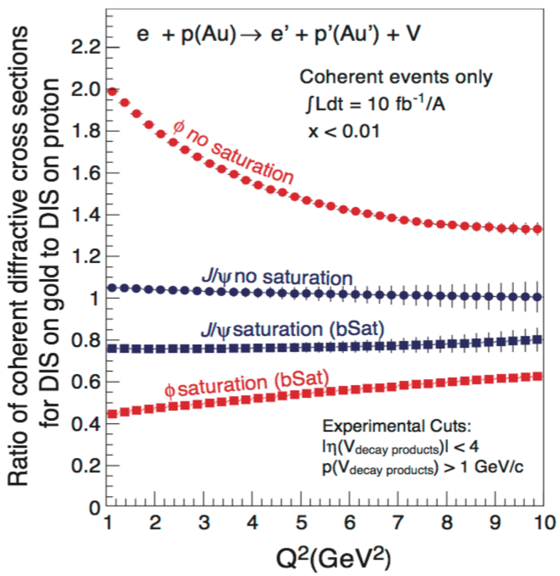
- Good momentum- and angular resolution
  - **Free neutron structure through spectator tagging**, imaging
  - Both in roman pots and fixed detectors

An example: Diffractive DIS (DDIS)

Signature for Saturation (among other things)



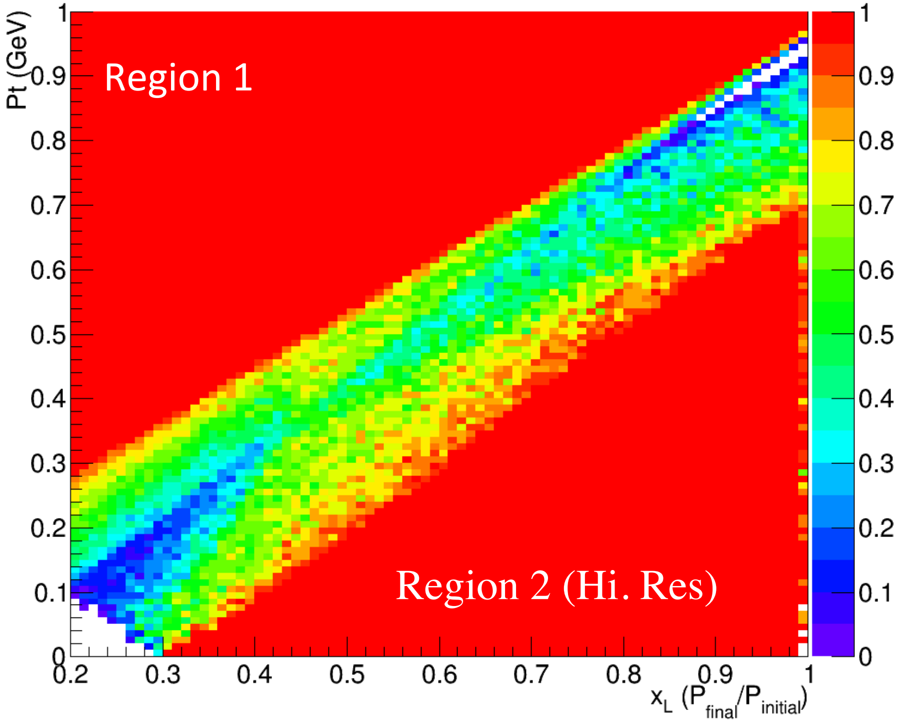




Identify the scattered proton: distinguish from proton dissociation
Measure $X_L = E_p'/E_p$, and P_t (or t) (equiv. to measuring M_x)

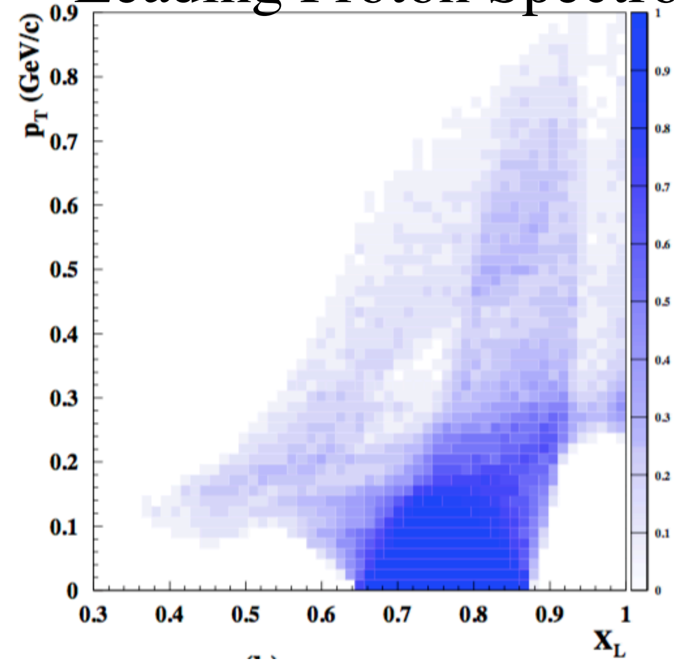
Acceptance for p’ in DDIS

JLEIC acceptance



Zhiwen Zhao

ZEUS
Leading Proton Spectrometer



Acceptance in diffractive peak (X_L>~.98)
ZEUS: ~2%
JLEIC: ~100%

Epilogue

Status of the EIC project

Nuclear science long-range planning

- Every 5-7 years the Nuclear Science community produces a Long-Range Planning (LRP) Document
- Previous versions:
  1979, 1983, 1989, 1996, 2002, 2007
- The final document includes a *small* set of recommendations for the field of Nuclear Science **for the next decade**
- *e.g.*, CEBAF 12 GeV Upgrade construction was the highest recommendation of the 2007 plan.

How does it work:

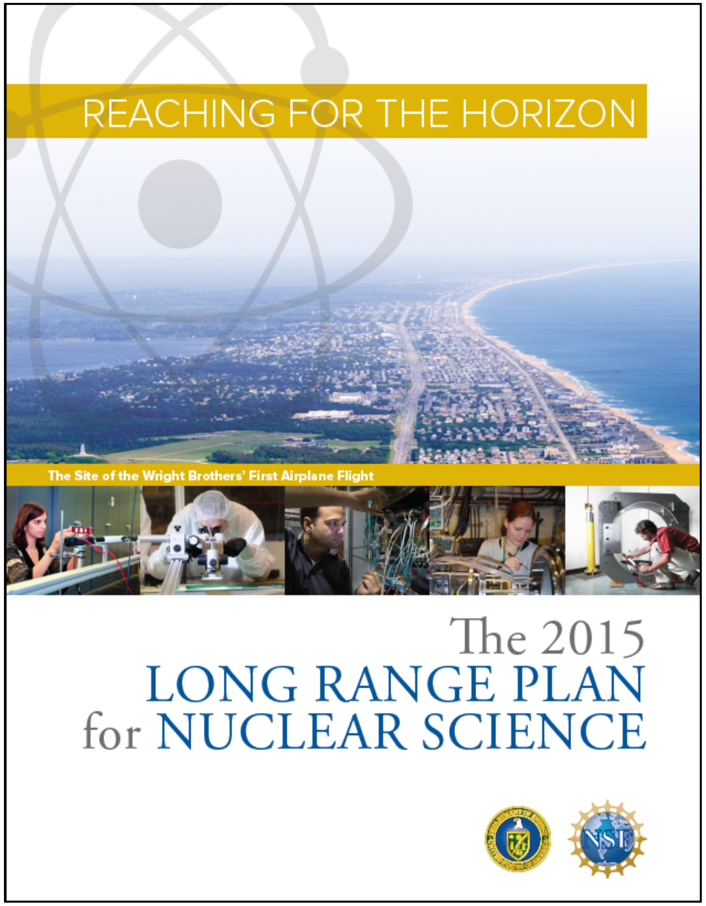
- The Division of Nuclear Physics of the American Physical Society organizes a series of Town Meetings, where the community provides input in the form of presentations and in the form of contributed "White Papers"
- Each Town Meeting produces a set of recommendations and a summary "White Paper"
- The Nuclear Science Advisory Committee, extended to about 60 people into a Long-Range Plan Working Group, then comes together for a week and decides on a final set of recommendations and produces a LRP document

Nuclear science long-range plan

Adapted from Don Geesaman (ANL, NSAC Chair) presentation
See: http://science.energy.gov/np/nsac/meetings/agenda20141117/

LRP Schedule

- ✓ Charge delivered at 24 April 2014 NSAC Meeting
- ✓ LRP Working Group formed in early June of ~60 members
  - NuPECC (Europe) and ANPhA (Asia) observers included
- ✓ Community organization Summer 2014
- ✓ DNP Town Meetings in the July/September 2014 time frame
- ✓ Joint APS-DNP-JPS Meeting Oct. 7-11, 2014, Wednesday afternoon discussion
- ✓ Working Group organizational meeting Nov. 16 in Rockville, MD
- ✓ Time for more community meetings in November-January
- ✓ (Community) White Papers by end of January, 2015 to have greatest impact
- ✓ Cost review of EIC by February 2015
- ✓ Most of text of report assembled by April 10, 2015
- ✓ Resolution meeting of Long Range Plan working group April 16-20, 2015
- ✓ Draft report reviewed by external wise women and men
- ✓ LRP final report finalized October 2015
  (Unanimously accepted at NSAC meeting October 15)



Recommendations

Exact text in final long-range plan report, shown here partial only

1. **The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.**
   - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
   - **FRIB** – understanding of nuclei and their role in the cosmos
   - **Fundamental Symmetries Initiative** – physics beyond the SM
   - **RHIC** – properties and phases of quark and gluon matter

   The ordering follows the priority ordering of the 2007 plan.

2. **We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.**

3. **We recommend a high-energy high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.**

4. **We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.**

EIC realization

With this formal NSAC/LRP recommendation, what can we speculate about any EIC timeline?

- It seems unlikely that a CD0 (US Mission Need statement) will be awarded without a National Academy of Sciences study (ongoing)

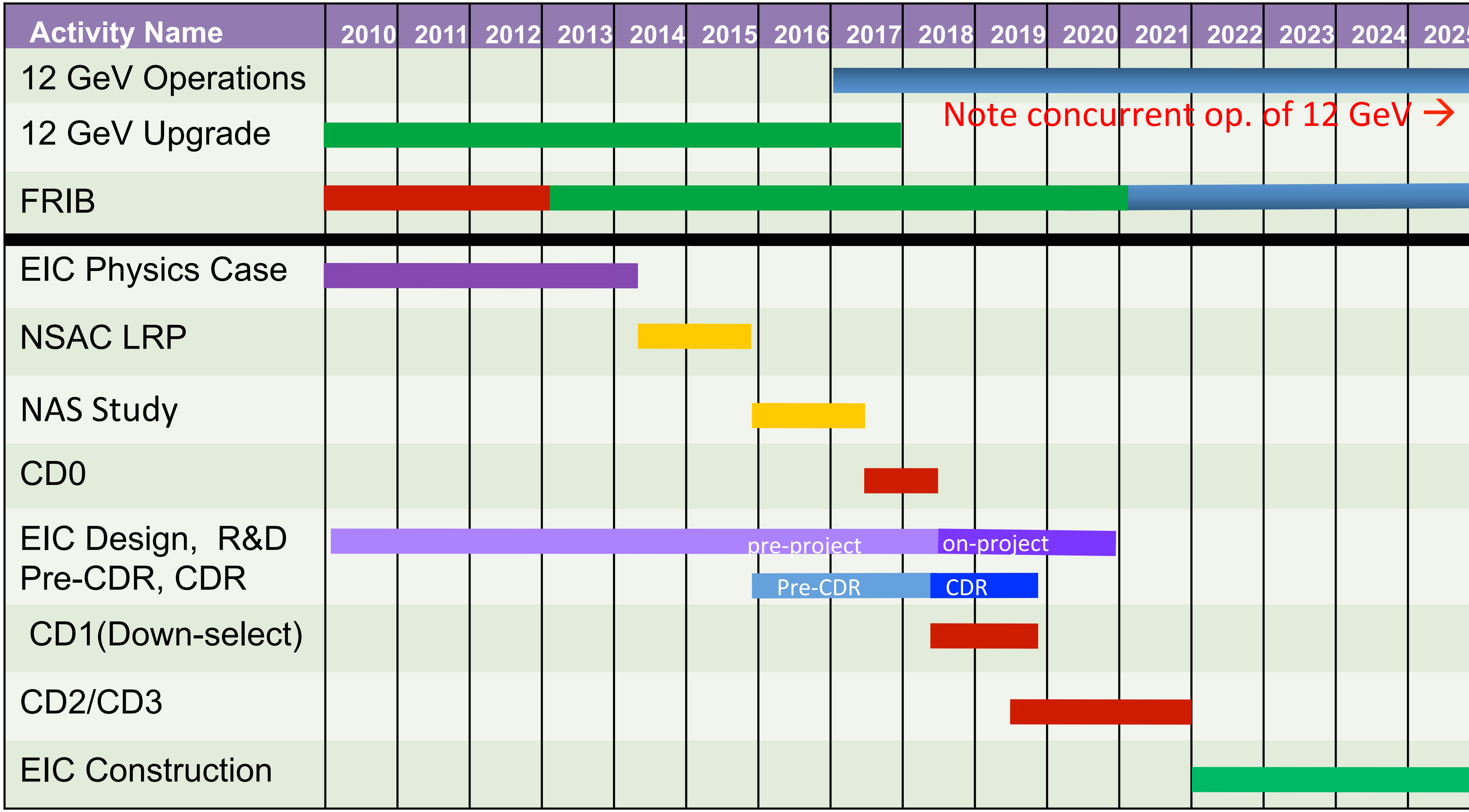
- EIC accelerator R&D questions will not be completely answered until ~2017

- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20

→ <u>Most optimistic</u> scenario would have EIC construction start (CD3) in FY20

→ Best guess for EIC completion would be 2025-2030 timeframe

EIC timeline (for JLEIC planning)



CD0 = DOE "Mission Need" statement; **CD1** = design choice and site selection (VA/NY)
CD2/CD3 = establish project baseline cost and schedule

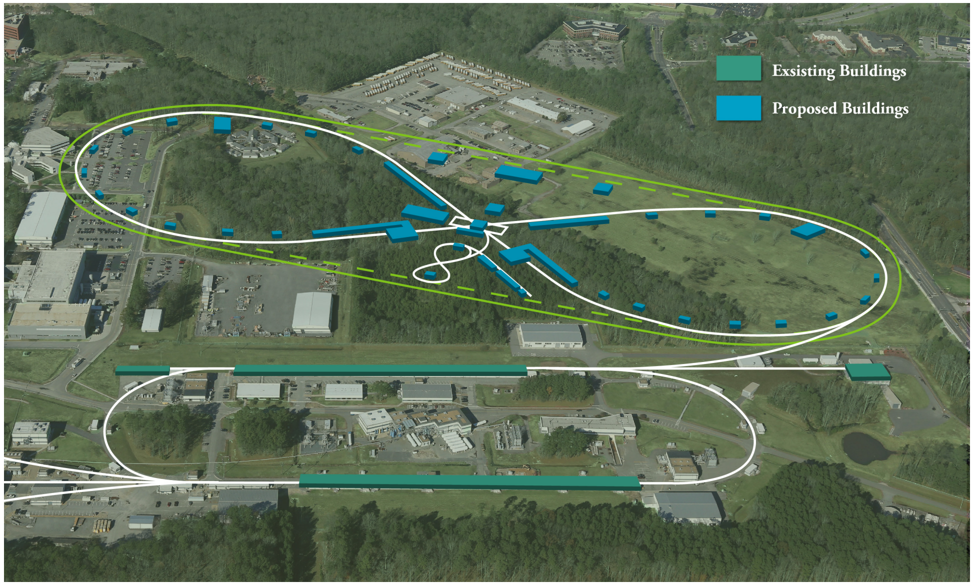
EIC User Group

EIC User Group (http://www.eicug.org)
Currently **651 members** from **143 institutions** from **27 countries**.

Nuclear Physicists around the world are thinking about and defining **the EIC research program**.

Conclusion: EIC and the future of NP

- **When the EIC is built, it will be *the* new NP machine for many decades.**
- EIC could revolutionize NP — but only if we build the right machine/detector.
- Accelerator Physicists, Experimentalists, and Theoreticians are thinking about and defining the EIC research program. It's important that many labs and universities - not only from within the NP community - get involved.
- If we do it right, this machine will enable fruitful and possibly revolutionary research for the 21st Century.



Thanks to:

Rolf Ent, Charles Hyde, Pawel Nadel-Turonski, Bob McKeown, Hugh Montgomery, Christian Weiss, **Rik Yoshida** for many discussions and help with preparing the talk.


Thank you very much for your attendance!